NASA CR-54109

Final Report

# CATHODE LIFETIME STUDIES



by

William Sirois

prepared for
National Aeronautics and Space Administration

Contract NAS 3-3563



ION PHYSICS CORPORATION

A Subsidiary of High Voltage Engineering Corporation

BURLINGTON, MASSACHUSETTS

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# FINAL SUMMARY REPORT

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

August 31, 1964

CONTRACT NAS 3-3563

Technical Manager
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Spacecraft Technology Division
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Burlington, Massachusetts

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## ABSTRACT

Experimental and analytical studies designed to determine the performance and reliability of indirectly-heated nickel matrix cathodes as electron sources in ion engines are described. Cathode performance has been evaluated in vacuum diodes and in simulated ion engines operating on mercury. The quality assurance plan under which the cathodes were fabricated and tested has been described in an earlier report. The results of both the temperature cycling (simulated pulsed operation) and mercury lifetime (d.c. engine operation) tests are presented. This program has shown the present heater geometry to be unsatisfactory for the engine application. The problem of emission degradation of this type of cathode, observed at other facilities, is discussed.

Author

## 1. INTRODUCTION

The incorporation of indirectly-heated nickel matrix cathodes, developed under NAS8-858[1] and NAS8-2513,[2] into the Lewis "Electron-Bombardment" engine, and investigated at this facility under NAS8-1684,[3] contributed significantly to the stability and reproducibility of the engine's performance over a series of short-term (~ 5 hour) runs. The performance characteristics of these units in an arc environment have been documented in earlier project reports. A number of cathodes* were also subjected without incident to the vibration schedule used in the SERT evaluation program. The total performance of the geometry recorded in these earlier projects demonstrated that the cathode had capabilities compatible with the engine requirements. However, the number of cathodes tested, and the periods of controlled testing in ion engines had been relatively small at the time of completion of NAS8-2513. It was

*No vibration tests were conducted under NAS3-3563.

therefore decided by NASA and IPC that the next logical phase of cathode studies would be one in which the cathode design at its then present state of development (Fig. 1) would be "frozen." The program was designed to provide test data in sufficient quantity and quality to yield meaningful lifetime and reliability figures.*

As the cathode is an integral component of the ion engine, it was also logical that the structure of the tests be based upon future ion engine requirements. Consequently, the cathode tests were based upon differing modes of operation that are likely to be required in the near future: one characterized by frequent interrupted d.c. operation as encountered in stationkeeping satellite programs while the other mode, continuous d.c. operation, to provide data for guidance in evaluation of the cathode for the extended d.c. operation demanded for interplanetary missions. Considerations, mainly of cost, and of time, and of the possibility that too many variables might submerge a true evaluation of the cathodes, precluded actual ion engine operation. However, it was felt that the arc behavior of the cathode in both the continuous and the interrupted d.c. operation could be adequately analyzed in the arc chambers of a multi-array of simulated 3 kW ion engines operating on mercury. Furthermore, the heater element, the most critical structural component of the cathode assembly, could be evaluated under accelerated temperature cycling conditions. Because the heater element is effectively shielded from the test environment, it was decided that any temperature cycling tests could be conducted in a vacuum environment. To assure that variables introduced by cathode fabrication processes and test data acquisition techniques would be minimized, a quality assurance program was an integral part of the effort.

*Concurrent with NAS3-3563, indirectly-heated nickel matrix cathodes have been studied in a program funded by IPC. One outcome of this program has been a heater element configuration that has demonstrated much greater reliability than the one currently in use.

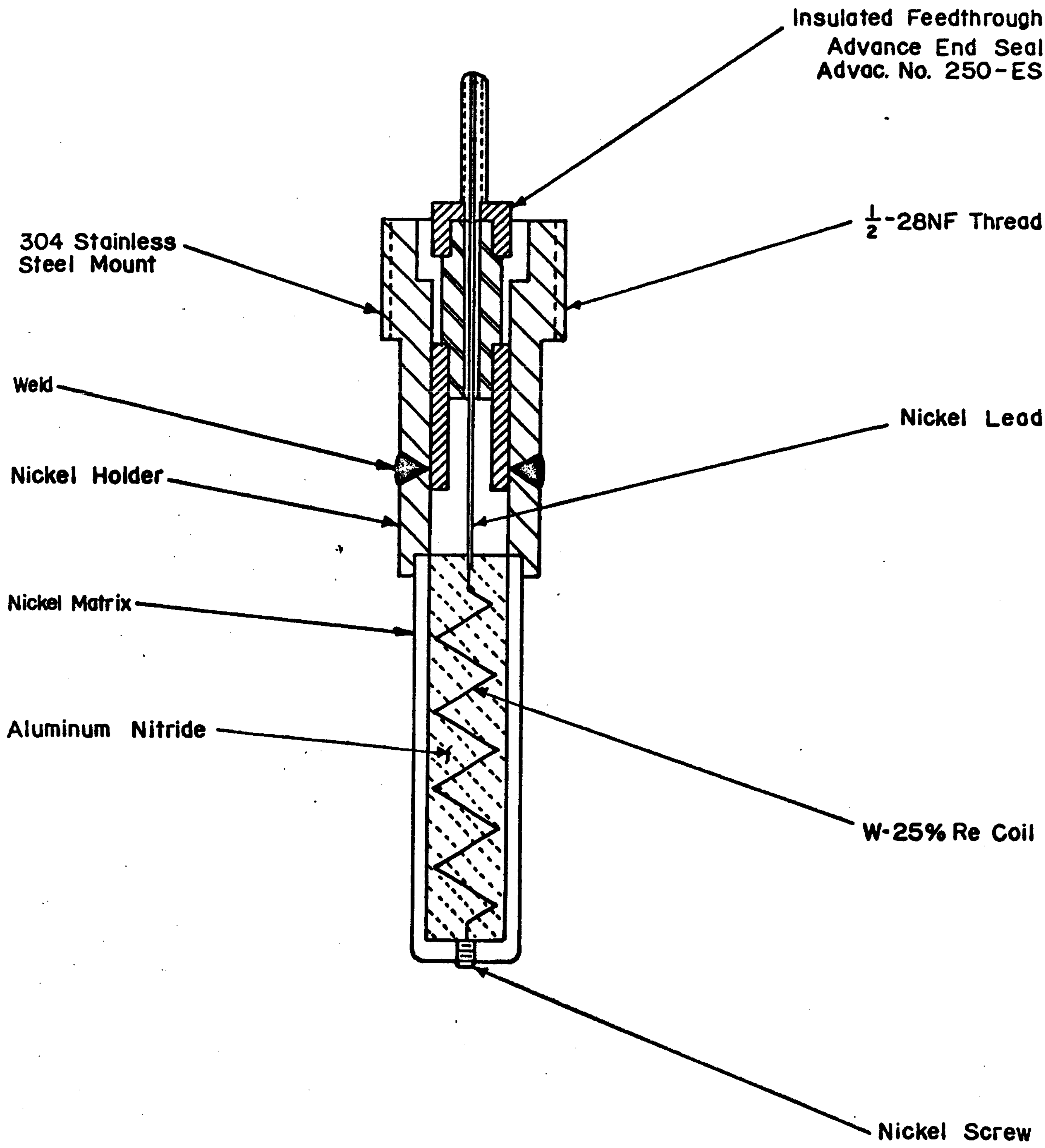


FIG. 1- L.C.D. ENGINE CATHODE TYPE 3

## 2. GENERAL TEST PHILOSOPHY

This summary report describes the work performed during the period from May 17, 1963 to March 30, 1964. This contract was a continuation of Contract NAS 8-2513.[2]

The basic objective of this program was to determine performance figures (reliability, lifetime) for the indirectly-heated nickel matrix cathode for two specific modes of operation:

(1) in the arc chambers of simulated 3 kW Lewis-type electron-bombardment engines; and

(2) under accelerated temperature cycling schedules.

To implement these studies a quality assurance plan was established during the first month of the contract and adhered to throughout the program. The plan essentially formalized cathode fabrication and test procedures and is detailed in the manual.[4]

The work schedule for the test program is shown in Table 1 and was planned to provide for a five-month period of systems fabrication and check-out (Parts I-IV) and seven-months of tests (Parts V-VI). These systems will be described in detail in Sections 3 and 4 but consisted basically of: (1) two hard-vacuum test systems, used for both the heater (cycled) life tests and final cathode conditioning and (2) the large mercury environment test system which consisted of 12 x 2.5 kW simulated engine configurations. This latter system was used for cathode testing under mercury vapor, field, and thermal conditions approximating those of the Lewis bombardment engine geometry.

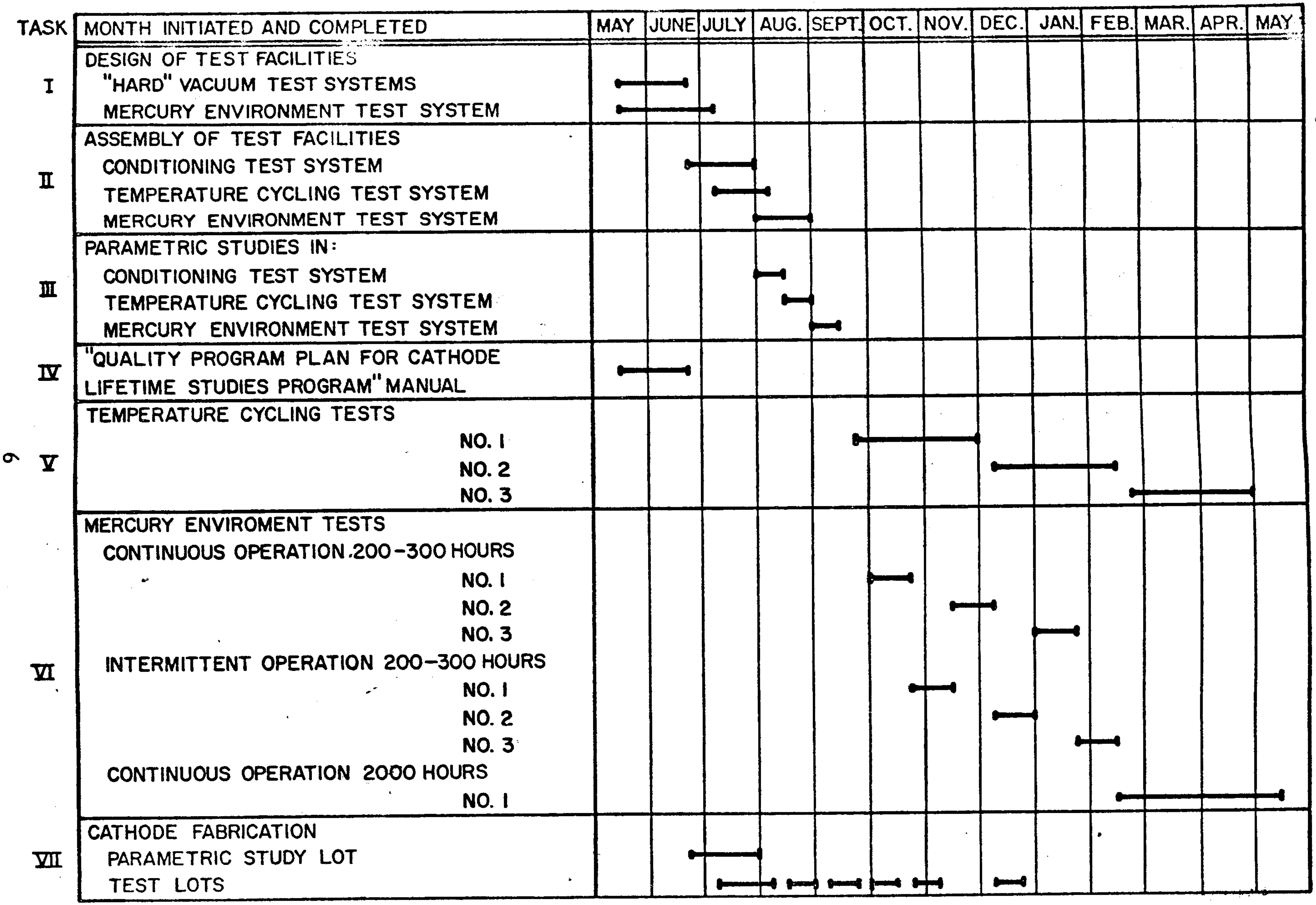


TABLE I WORK SCHEDULE FOR CATHODE LIFETEST PROGRAM

As indicated in Part VII of Table 1, cathode fabrication continued on a lot (24 cathodes each) basis throughout the first eight months of the program. Some 120 cathode assemblies were completed during this period for the several (6) test lots (A-F) in addition to the initial lot used for system check-out and evaluation (parametric studies). As shown in Table 2, the tests were planned to proceed with the following cathode distribution:

(V) Temperature Cycling Life Tests 1-3: Six cathodes from each of lots A and B, C and D, E and F to be grouped in test lots of 12 and each lot was to be subjected to at least 25,000 thermal cycles.

(VI-a) Continuous Mercury Life Tests: Six cathodes from each of lots A and B, C and D, E and F to be grouped in test lots of 12 and each lot subjected to at least 200 hours of simulated continuous mercury bombardment engine operation.

(VI-b) Intermittent d.c. Mercury Life Tests: Six cathodes from each of the 6 lots to be grouped in test lots of 12 and subjected to intermittent d.c. mercury life tests for a period of at least 200 hours.

(VI-c) Extended Mercury Life Tests: Two cathodes from each of the 6 lots to be subjected to an extended lifetime run.

The parametric studies accomplished during the early part of the test program pointed up several difficulties implicit in the parallel operation of 12 units in the mercury life test system. The temperature cycling tests, in turn, demonstrated a basic weakness of the heater-insulator configuration to extended operation in this mode. As a result, only parts of the total planned work program (V and VI-a) were completed in the ten-month effort. These results and the systems upon which they were taken will be described in the following sections.

Table 2 - Outline of Cathode Life Test

| CATHODE LOT - FABRICATION NUMBER | | A | B | C | D | E | F |
|---|---|---|---|---|---|---|---|
| TOTAL NUMBER CATHODES FAB. PER LOT | | 24 | 24 | 24 | 24 | 24 | 24 |
| V Temperature Cycle Life Test | Life Test No. 1 | 6 | 6 | | | | |
| | 2 | | | 6 | 6 | | |
| | 3 | | | | | 6 | 6 |
| VI Continuous DC Mercury Life Test | 1 | 6 | 6 | | | | |
| | 2 | | | 6 | 6 | | |
| | 3 | | | | | 6 | 6 |
| Intermittent DC Mercury Life Test | 4 | 6 | 6 | | | | |
| | 5 | | | 6 | 6 | | |
| | 6 | | | | | 6 | 6 |
| Extended Mercury Life Test | 7 | 2 | 2 | 2 | 2 | 2 | 2 |
| Total No. Cathodes Life Tested / Lot | | 20 | 20 | 20 | 20 | 20 | 20 |

Note: Four extra cathodes from each lot are to allow for any rejects in fabrication.

# 3. DESCRIPTION OF THE TEST SYSTEM

## 3.1 HARD VACUUM CONDITIONING/HEATER TEST SYSTEM

Two systems of identical design were constructed for the hard vacuum ($\sim 10^{-6}$ torr) environmental tests. One system in which the cathodes were conditioned is pictured in Figs. 2 and 3. The twin system in which heater lifetime tests were conducted is shown in the foreground of the photograph in Fig. 4.

Basically, each system consisted of 2 identical 304 stainless steel cylindrical test chambers, a central multi-port chamber, pumping devices and accessories, and the related power supplies and circuits.

Each test chamber, the measurements of which were 12 inches in length and 6 inches in diameter, contained a mounting structure in which 6 cathodes and anodes were installed. The spacing between the cathodes and the concentric cylindrical stainless steel anodes was 0.060 inch.

Each test chamber was also equipped with a sight port. Through the port, temperature measurements of the cathodes could be made with the aid of an optical pyrometer. To allow temperature measurements to be taken during the periods when the anodes were in position, each anode had a centrally located 1/8-inch diameter hole in its surface. An important step in all anode installations was the alignment of these holes with pre-arranged sight paths.

The multi-port chamber was basically a "cross" constructed of aluminum and contained four 6-inch diameter ports. Two ports supported the cathode-anode mounting structures and the stainless test chambers already described. The third port served as an entrance area for the various power

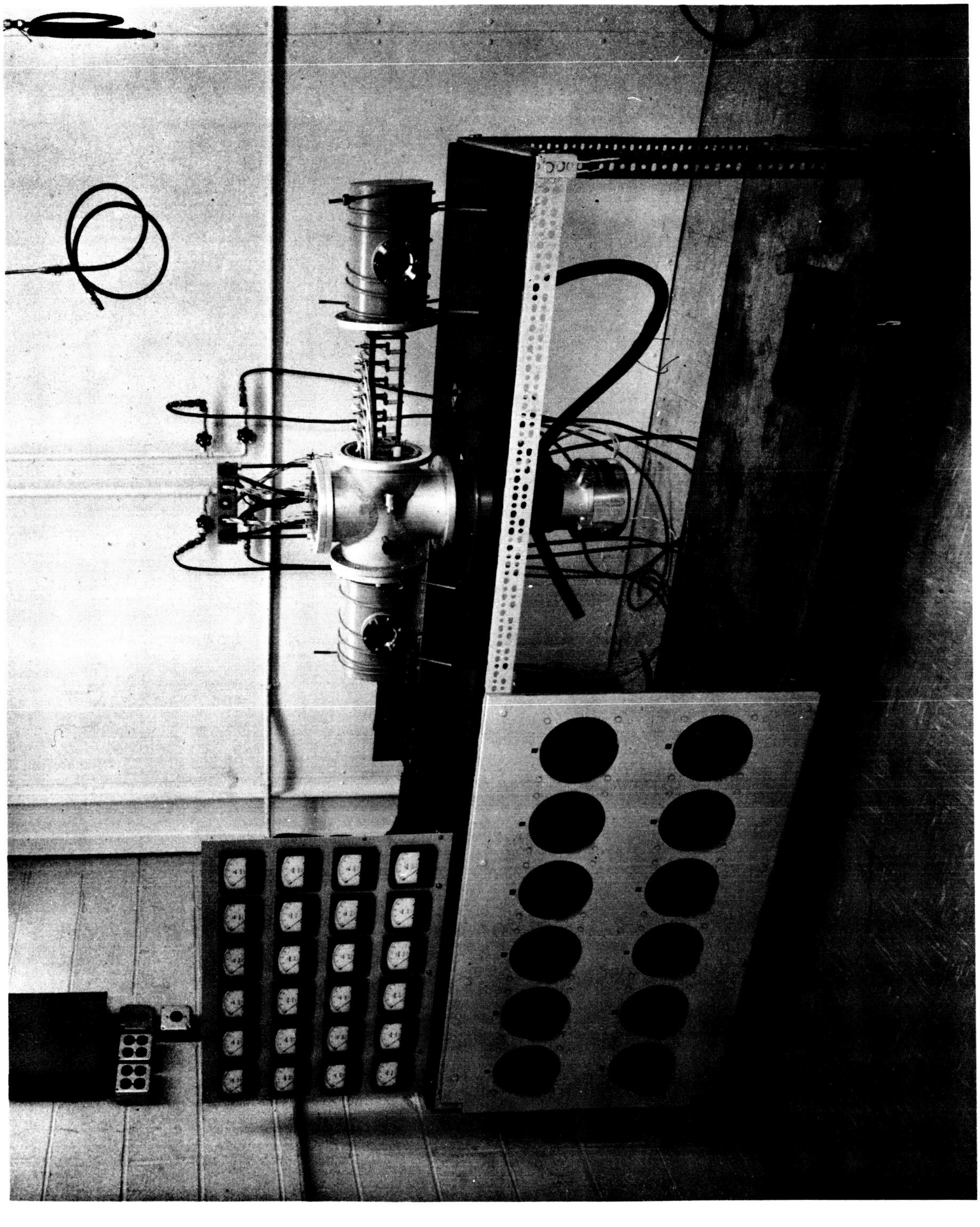

FIG. 2 VIEW OF THE CONDITIONING TEST SYSTEM

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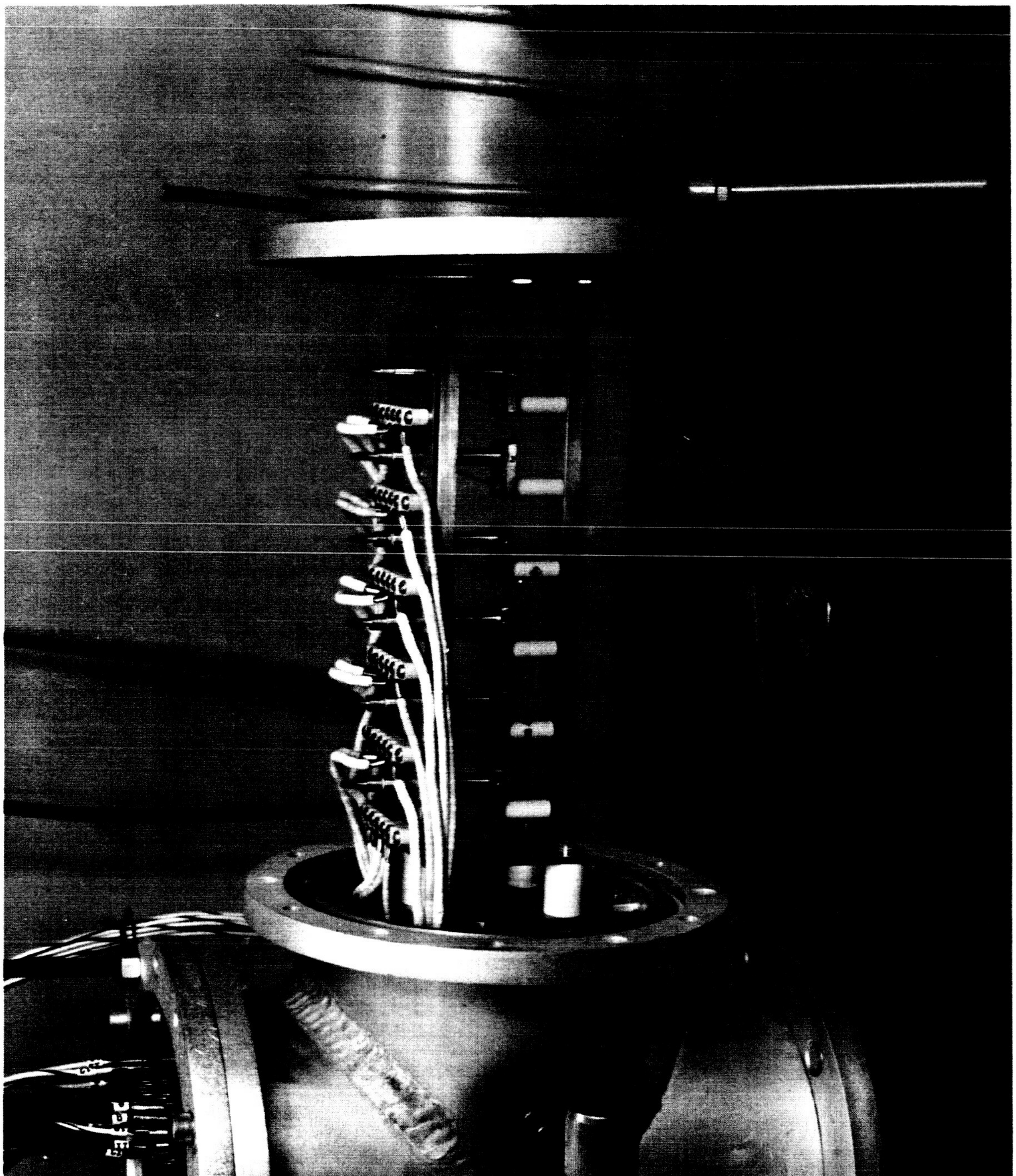

FIG. 3 CLOSE-UP VIEW OF ONE OF THE TEST CHAMBERS OF THE CONDITIONING TEST SYSTEM

2-212

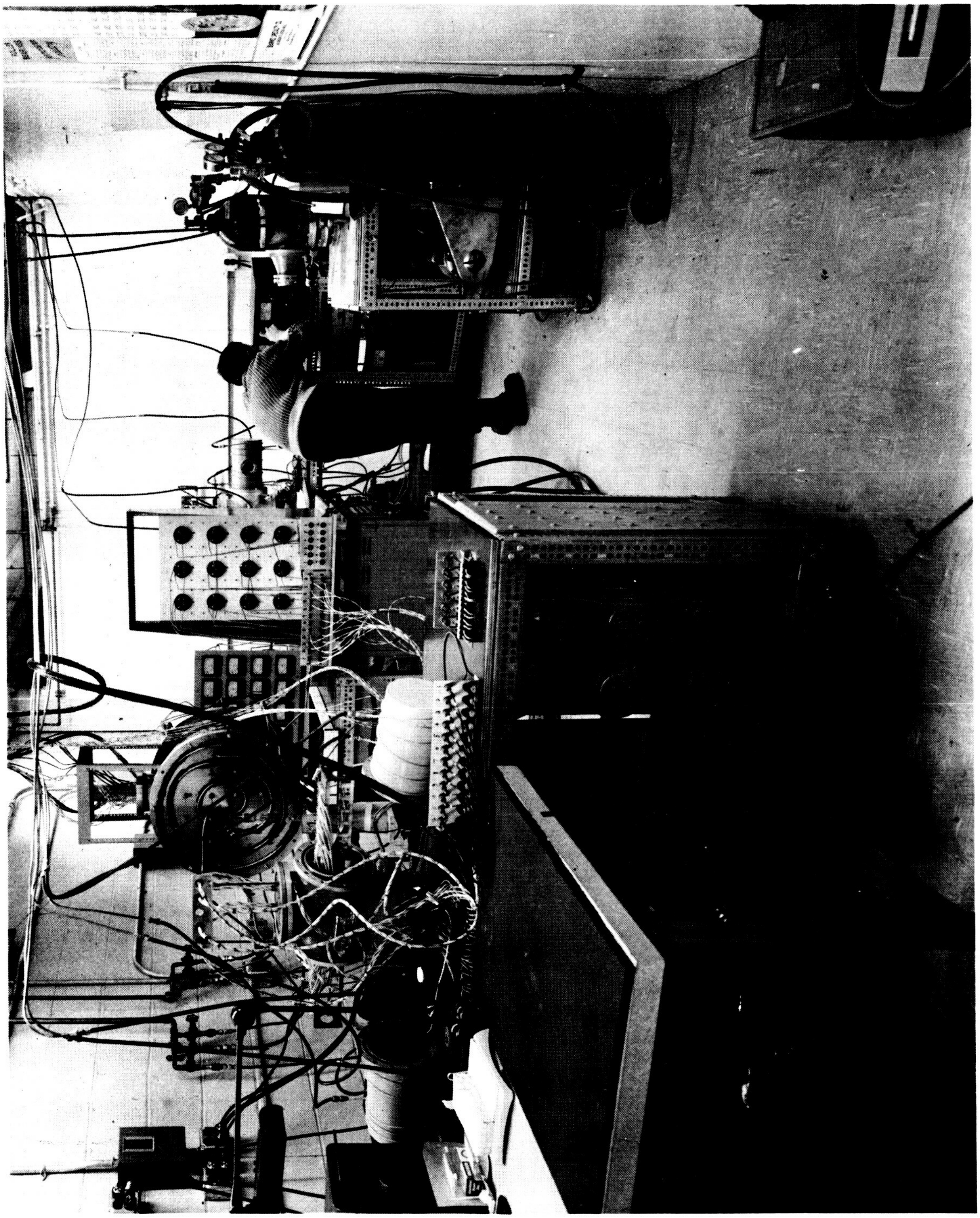

FIG. 4 VIEW OF THE CATHODE TEST FACILITY

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cables. The fourth port led to the pumping system. The chamber also contained a thermocouple gauge and an ionization gauge.

A 4-inch diameter oil diffusion pump, a freon-refrigerated "ballast-type" baffle, both products of National Research Corporation, and a Kinney mechanical pump comprised the main portion of the pumping system. Also included in the pumping system were 2 electrically operated vacuum solenoids. One solenoid was placed between the diffusion pump and the roughing pump, and the other between the roughing pump and the atmosphere. In the event of a power failure, the former would "close" and maintain the vacuum in the test chamber while the latter would "open" and allow the roughing pump to vent to the atmosphere. In addition, all the power supplies including those that energized the solenoids were routed through holding relays that, once broken, required manual resetting. These safety features were also incorporated into the mercury test system which is discussed in the following section.

A schematic of the electrical test circuit for both systems is shown in Fig. 5.

## 3.2 MERCURY LIFETIME TEST SYSTEM (12 MODULE)

The first objective of this contract was to evaluate cathodes in the arc chambers of simulated Lewis "Electron-Bombardment" engines. The NASA electron-bombardment engine was first tested by Kaufman at the NASA Lewis Research Center.[5] Operating characteristics of engines of this type (commonly called "low current density" engine or LCD engine) have been investigated at this facility under Contract NAS8-1684.[3]

The basis of the engine is an axially confined discharge which produces a plasma composed of the propellant ions and electrons. These ions are focused into a beam at the screen or beam forming electrode and are then electrostatically accelerated to the correct specific impulse, producing the

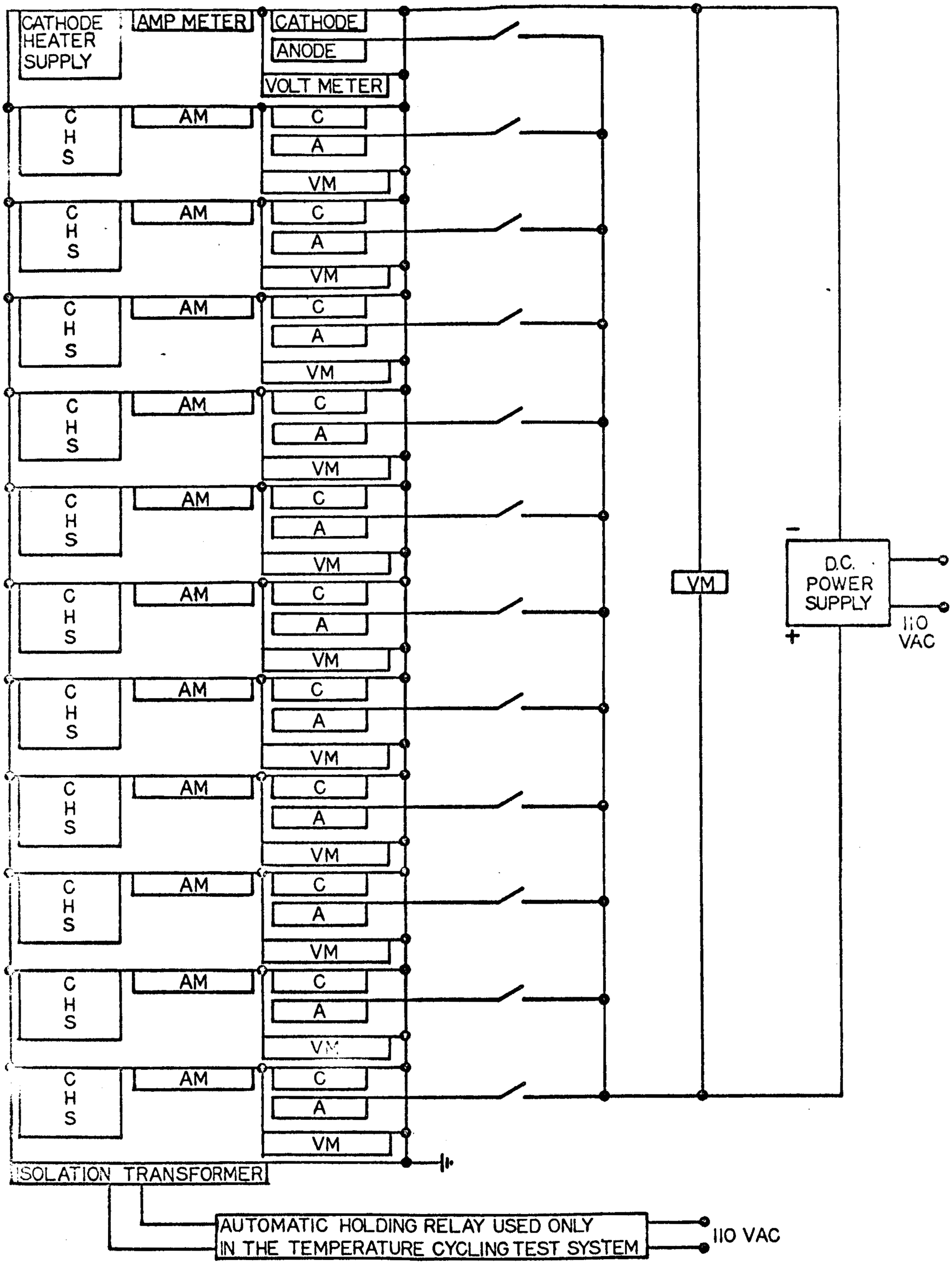


**FIG. 5 ELECTRICAL TEST CIRCUIT SCHEMATIC (CONDITIONING & TEMPERATURE CYCLING TEST SYSTEM)**

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desired thrust. The beam is subsequently decelerated by a small potential such that a barrier is presented near the last electrode to neutralization electrons which are injected just beyond the final electrode of the engine. The engine configuration is shown in Fig. 6.

In the design of the simulated ion engine (Fig. 7), the beam forming electrodes and the mercury boiler were omitted. The electromagnet was replaced by 4 symmetrically placed permanent magnets and the power requirements of the normal configuration therefore avoided. The magnets provided a suitable magnetic field for increasing the effective electron path length in the arc chamber, hence increasing the ionization probability. The field is of sufficient strength to bias the electrons beyond magnetron cut-off so that electrons are confined to circular orbits of a diameter less than the anode radius. Only electrons that have suffered a collision with a residual gas atom or ions will have their orbits perturbed sufficiently so that they can reach the anode.

The 2 peripheral heat shields have 2 functions. They are instrumental in allowing the anode to sustain temperatures (~ 450°C) reached in actual engine operation and they also aid in minimizing plasma coupling between individual "engines." The arrangement of the 12 engines is shown in Fig. 8.

Before this arrangement was approved, a wooden mock-up of the proposed support plate was constructed with accommodation for variable location of the permanent magnets. The resulting field distributions were then mapped over the cathode and accelerator electrode planes. It was found that the magnets could be arranged in such a manner that each "engine" cathode would be subjected to the same axial magnetic flux density at its surface. That figure is approximately 25 gauss and is of sufficient strength to confine emitted electrons from the cathode surface to circular orbits of a diameter less than the radius (3.7 cm) of the anode at an operating potential of 50 volts.

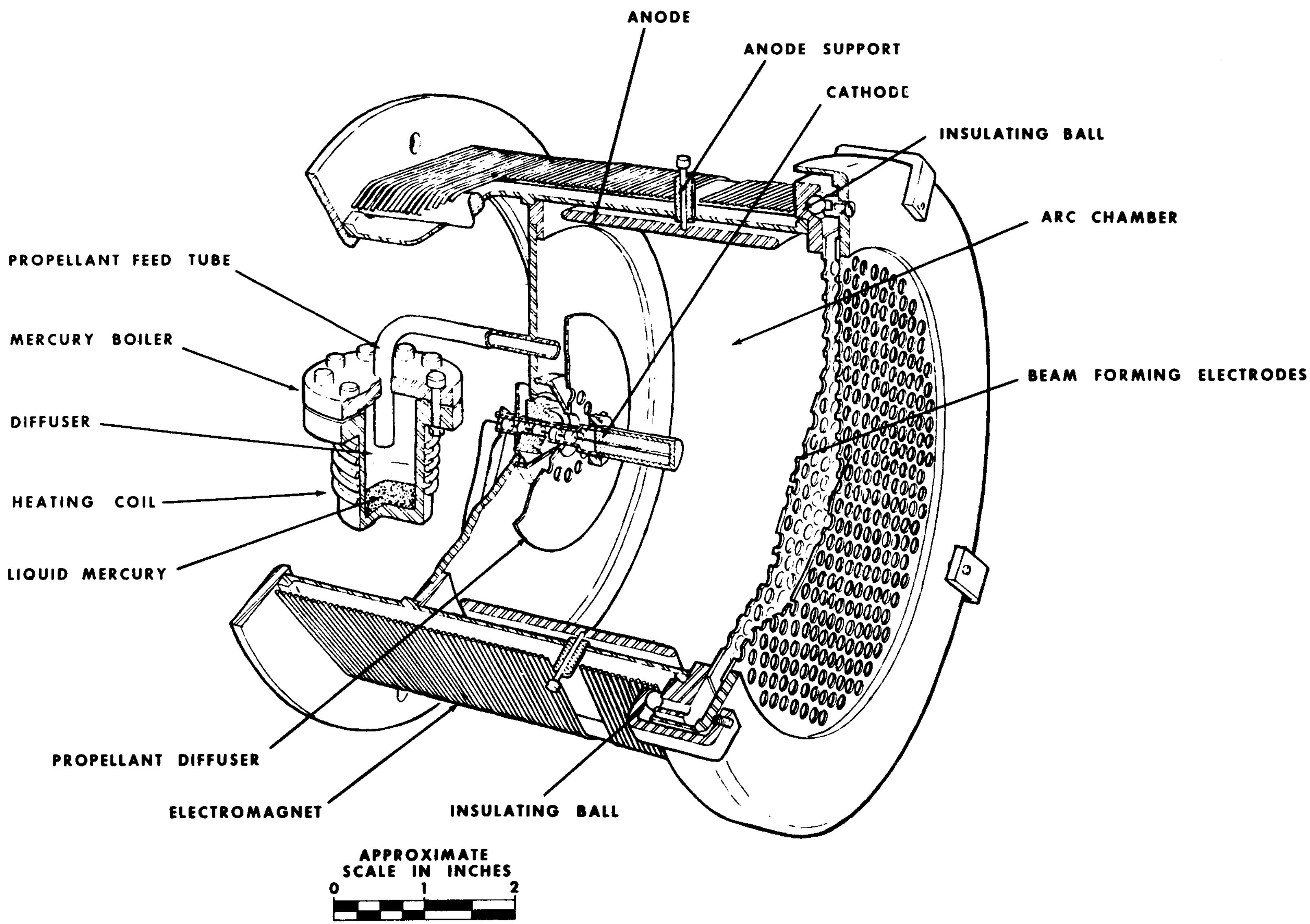
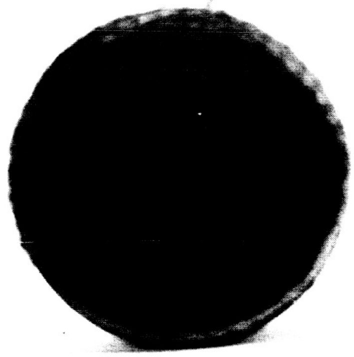
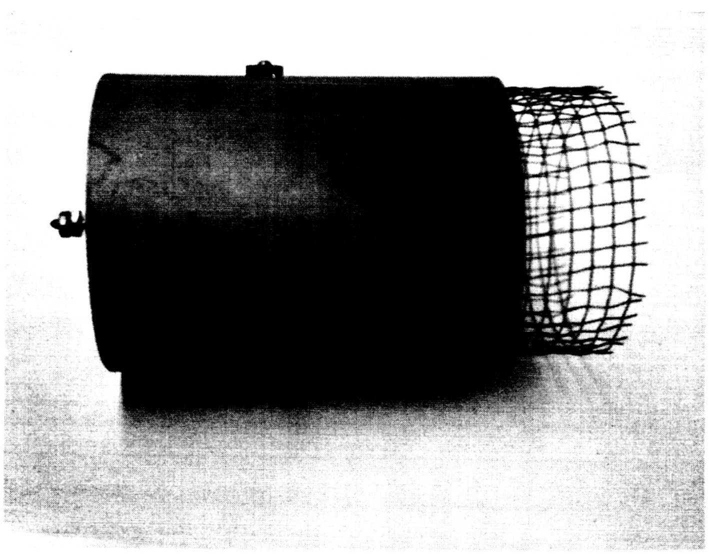



FIG. 6 LOW CURRENT DENSITY ION ENGINE



FRONT VIEW



SIDE VIEW

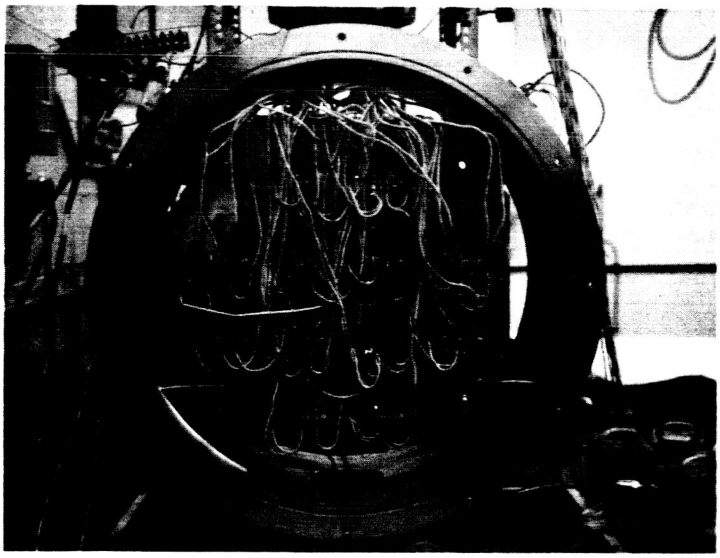
I-727 FIG. 7 VIEWS OF THE SIMULATED LOW CURRENT DENSITY ION ENGINE

The test chamber as shown in Fig. 8 was fabricated from 304 stainless steel and measures 24 inches in diameter and 12 inches in depth. The 4 inner tabs serve as mounting plates to which the support plate is fastened. Figures 9 and 10 show the designs of the 2 main flanges, both of which were also fabricated from 304 stainless steel. The 12 Edwards vacuum rotary seals which are installed in the rear end plate permit probe access to each arc chamber. Each sight port on the front access plate is coaxial with an opposing cathode. Several feedthrough ports were available both at the sides and top of the chamber.

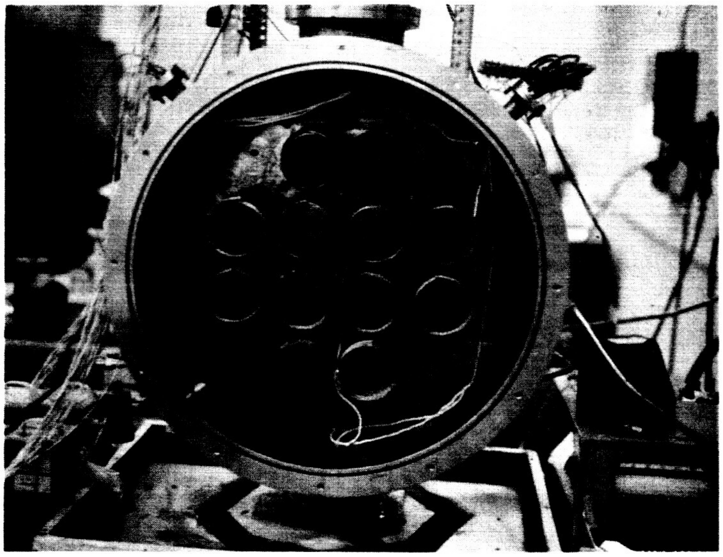
The pumping system consisted of a special freon-cooled baffle (whose walls could also be controlled with a dry ice/acetone system) and a 4-inch diameter mercury diffusion pump. A dry ice-cooled trap was used in the foreline to prevent contamination of the forepump.

The conventional propellant feed system for the LCD engines investigated at this facility consisted of a boiler, flow regulator, feed tube and propellant diffuser (see Fig. 6). A fixed mercury vapor pressure was produced in the boiler by thermal control. The conductance of the flow regulator, consisting of a small ($\sim 0.008$ inch) orifice, determined the flow rate of mercury vapor through the feed tube and into the arc chamber. Inside the arc chamber, the propellant distributor modifies the vapor flow such that for each propellant atom at least one collision with a wall must occur before exit.

The initial configuration by which the foregoing propellant feed system was to be simulated for the mercury life tests is illustrated by the block diagram of Fig. 11. The mercury vapor flow rate was to be controlled by the temperatures of the gravity-fed mercury boiler and the freon-cooled mercury baffle and by adjustments of the stainless steel valve which controlled the mercury level in the boiler reservoir. The water-cooled front panel had several purposes. First, mercury vapor and ions accelerated from the arc



REAR VIEW



FRONT VIEW

FIG. 8 VIEWS OF THE INTERIOR OF THE MERCURY LIFE TEST CHAMBER

I-732

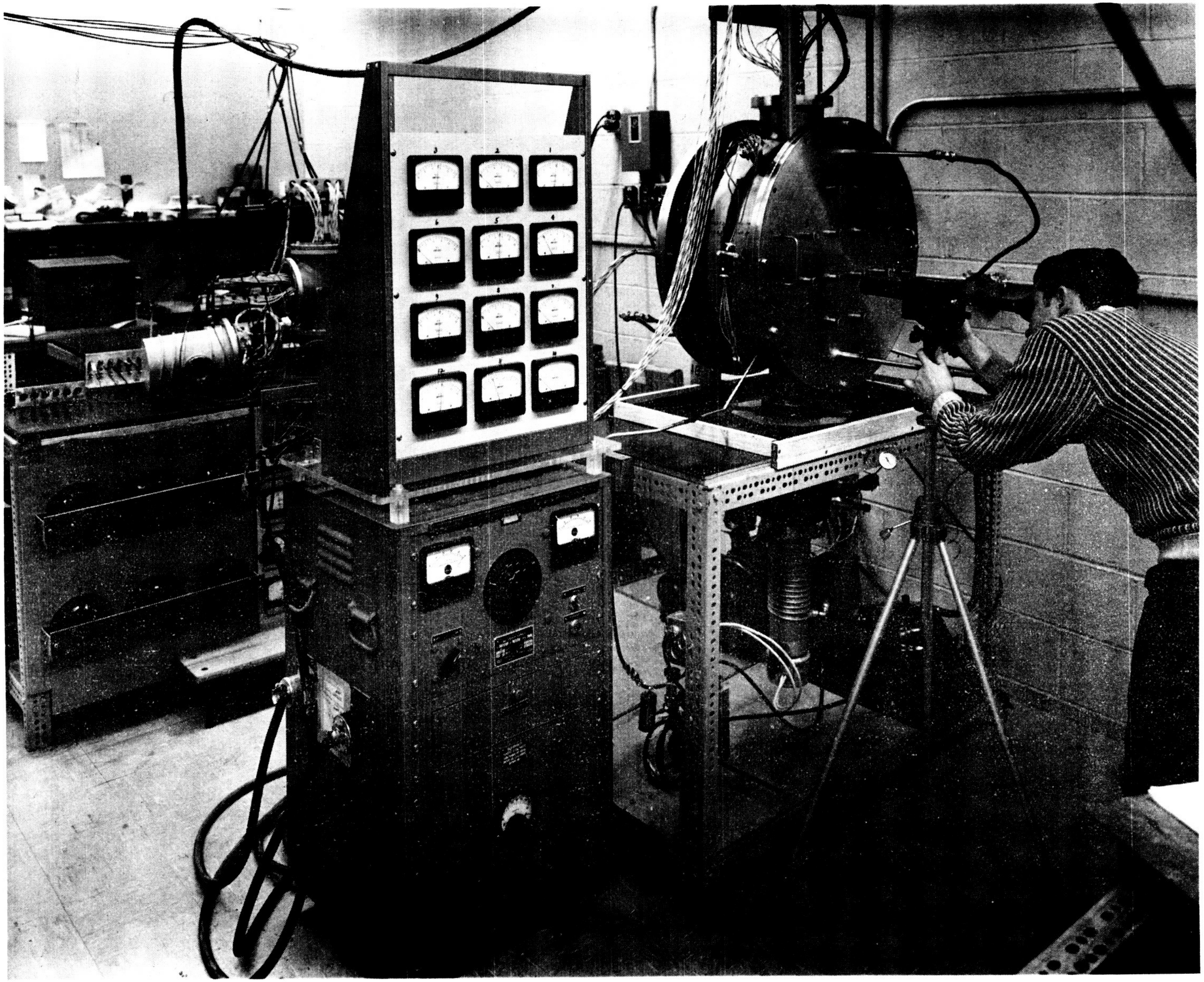


FIG. 9 VIEW OF THE MERCURY TEST SYSTEM (SIGHT PORT SIDE)

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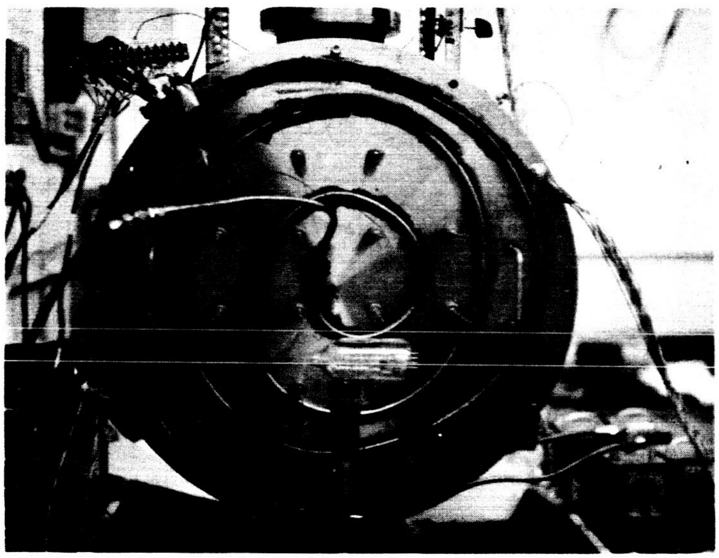

FIG. 10 VIEW OF THE MERCURY TEST SYSTEM (PROBE SIDE)

1-733A

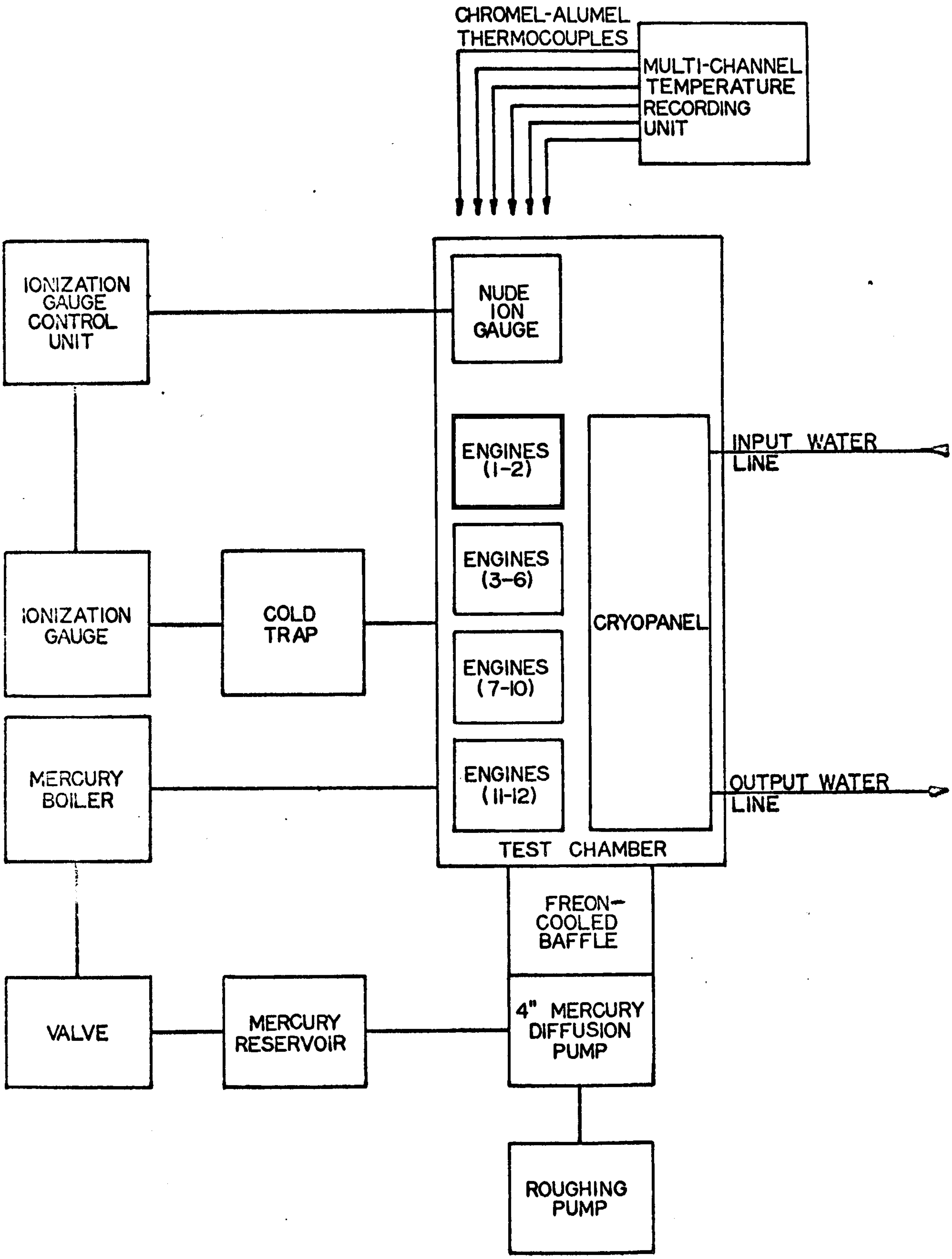


FIG. 11 BLOCK DIAGRAM OF THE INITIAL MERCURY LIFETEST SYSTEM



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could be reflected from its surface back into each arc chamber and second, it served as a primary shield for the sight port windows. Since it was to be the coolest surface in the system, it would control the inventory of mercury (and hence vapor pressure) in the system throughout each run.

After testing began, it became necessary to modify the system to that shown by the block diagram of Fig. 12. It was found that once arc operation commenced and arc chamber temperatures reached the range of 400 to 500°C, the chambers had a tendency to pump-out and to expel both ionized and neutral mercury atoms. This naturally lead to very unstable arc operation due to the large reversed pressure gradients existing across the apertures to each engine system. To overcome this phenomenon, it was necessary to create a condition in which mercury vapor was fed to each chamber from the cooled shroud such that a ready supply of vapor at elevated pressure was available for sustenance of the arc. This was done by lowering and controlling the temperature of the cold wall, thus producing an excess amount of condensed mercury on the shield panel surface which was available to each arc chamber.

The conductance of the original feed system into the test chamber proved to be inadequate. The by-pass line containing the boiler, reservoir, valve, and heated connection lines were ultimately removed. Mercury was supplied directly from the boiler of the mercury diffusion pump. This was accomplished by reducing the flow of freon to the mercury baffle once the major outgassing (pumpdown) of the test system had been completed. Effectively unbaffled, the ultimate mercury vapor pressure in the chamber would reach $1 \times 10^{-3}$ torr. To serve as an auxiliary source during start-up, a mercury boiler was attached to the cold panel.

The temperature of this panel was controlled in the following manner: its temperature was sensed by a thermocouple welded to its surface. Its output was used by a "pyrotroller" temperature control unit which was

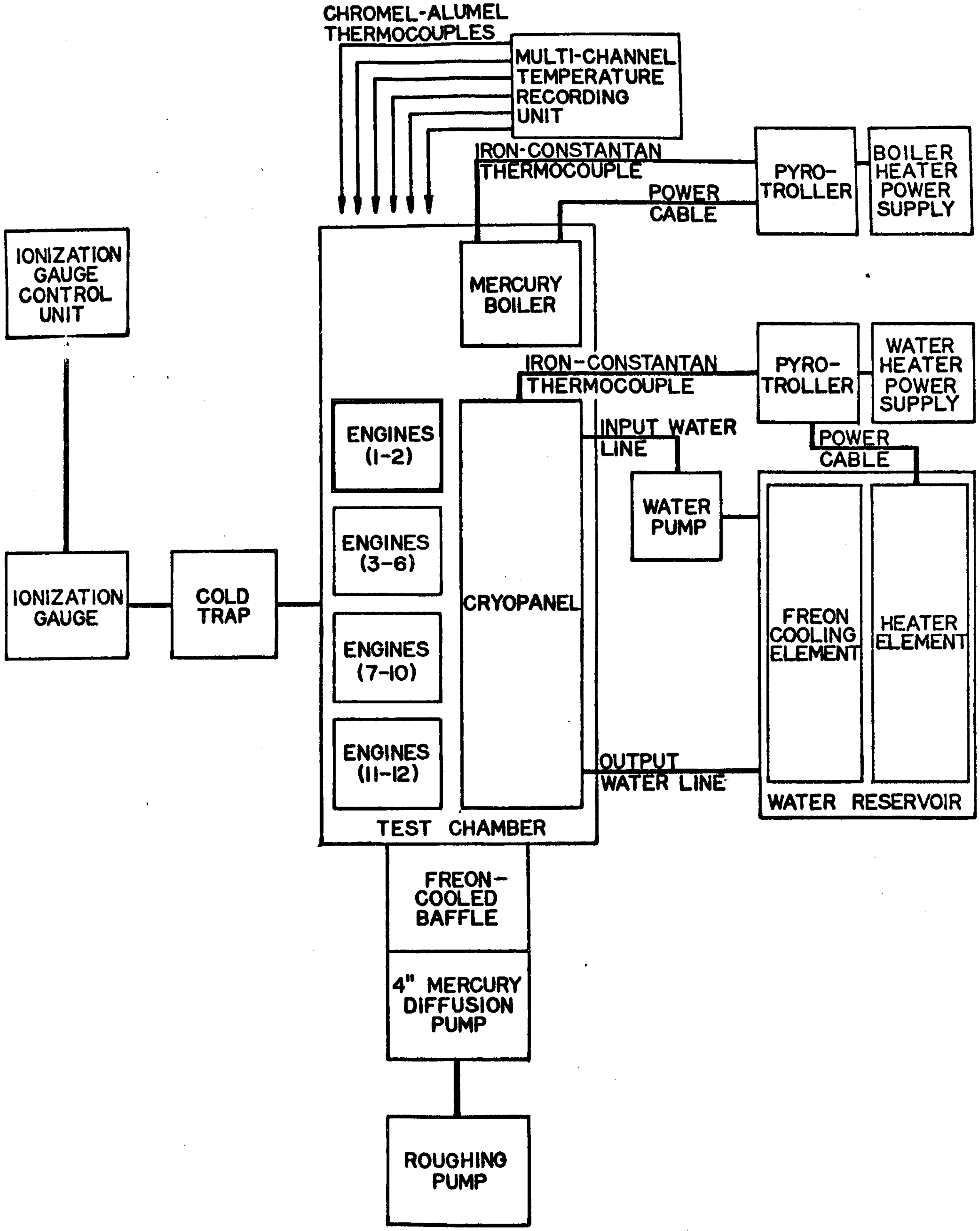


FIG. 12 BLOCK DIAGRAM OF THE MODIFIED MERCURY LIFETEST SYSTEM



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programmed such that the temperature was maintained within a narrow ($\pm 2°C$) range through control of an immersed heater element in the reservoir of the heat exchanger used in the panel coolant loop. Both the refrigeration unit and the water pump of the exchanger were in constant operation. The temperature of the boiler could also be controlled in the same manner. However, its lower temperature limit was governed by the cold panel since it was attached directly to that surface and shielded from radiative heating by the engine units themselves.

In addition to the sensing thermocouples on the cold panel and the boiler, other thermocouples were placed throughout the system, such as on the engine heat shields and the internally mounted support plate. The partial pressure of noncondensible gases was measured by an externally located trapped ion gauge. Previously, attempts had been made to measure the mercury vapor pressure inside the chamber with the aid of a nude ion gauge. However, the lifetime of the exposed gauge was severely reduced due to attack by the mercury atmosphere.

The schematic of the electrical test circuit for the mercury life tests is shown in Fig. 13. The circuit was so wired that any cathode or anode branches could be removed without affecting the remaining portion of the circuit. In one anode branch, the 2-ohm surge resistor was parallel with a 25-ohm resistor and a d.c. milliampere current recorder in series, thus permitting a constant record of arc performance.

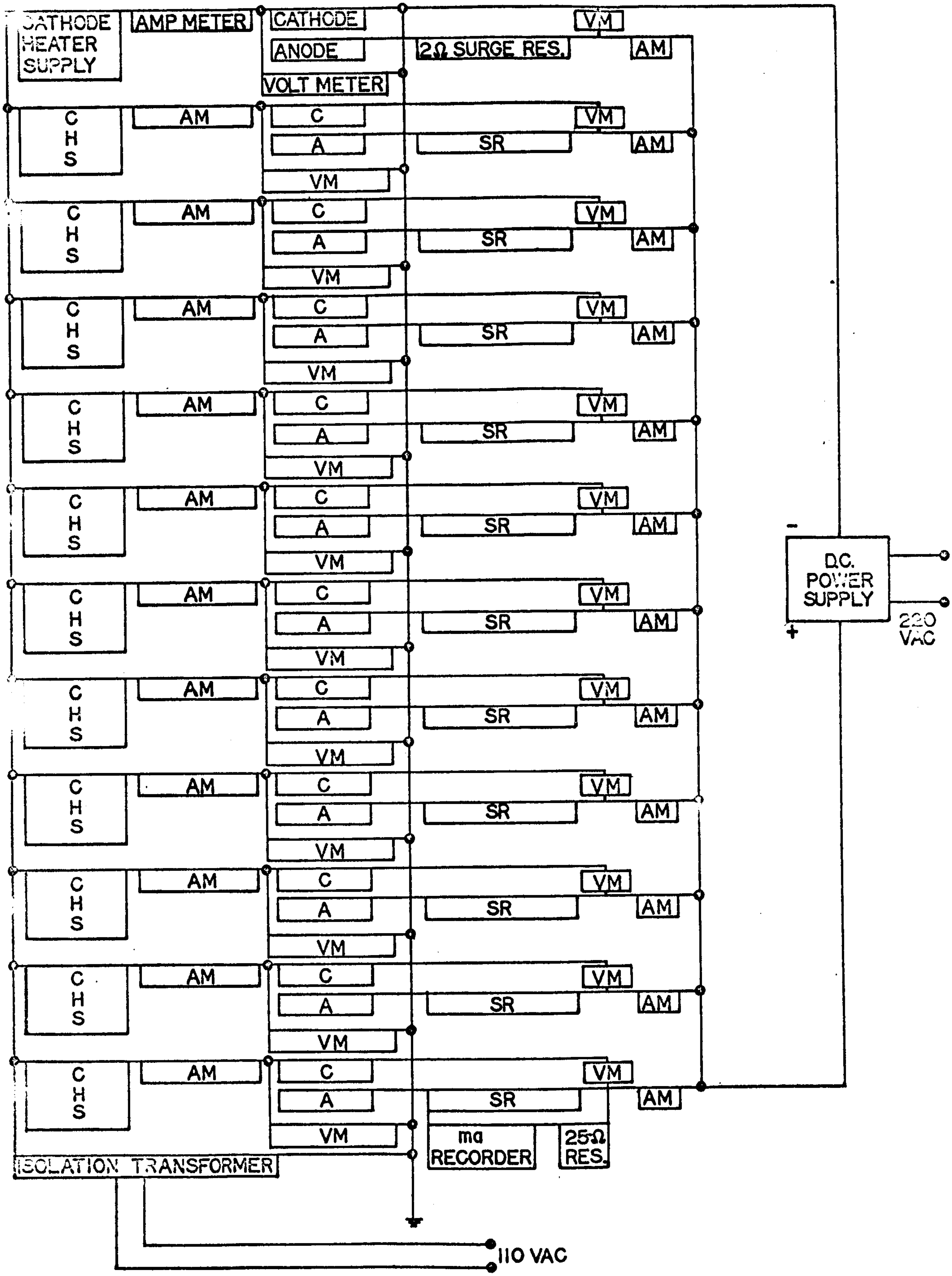


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FIG. 13 ELECTRICAL TEST CIRCUIT SCHEMATIC
(MERCURY LIFETEST SYSTEM)

# 4. PROCEDURES

## 4.1 FABRICATION TECHNIQUES

The procedures by which the indirectly-heated nickel matrix cathodes were fabricated are set forth in the manual.[4] In brief, the cathodes were fabricated in the following manner.

A mix containing carbonyl nickel powder (89% by weight), barium and strontium carbonates (10% by weight) and zirconium hydride, (1% by weight) was first tumbled for several days. The powder was next placed into surgical latex tubing and compacted into cylindrical slugs through isostatic pressing at a pressure of 30,000 psi. The slugs were then sintered in a hydrogen atmosphere. The sintering schedule in its entirety is shown in Appendix A. The results of machining, heater insertion, and final assembly, which were then accomplished under "clean" conditions, are illustrated in Fig. 14.

Although the Quality Control manual already mentioned formalized the basic fabrication techniques, the primary purpose of the quality control program with respect to cathode fabrication was to institute and maintain adequate process safeguards. The executions of these safeguards which covered handling, pressing, and machining techniques and involved numerous inspection points, ensured that all the cathodes produced under the plan would be "identical" in configuration and in material composition.

An example of the manner in which Quality Assurance was pursued is provided by the data in Tables 3, 4, and 5. These records were maintained for each of the cathode lots.

As originally scheduled (Table 1) the fabrication of a lot was expected to require an average period of 2 weeks. However, the execution of the Quality Control Plan and the inevitable rework necessitated by it more than doubled

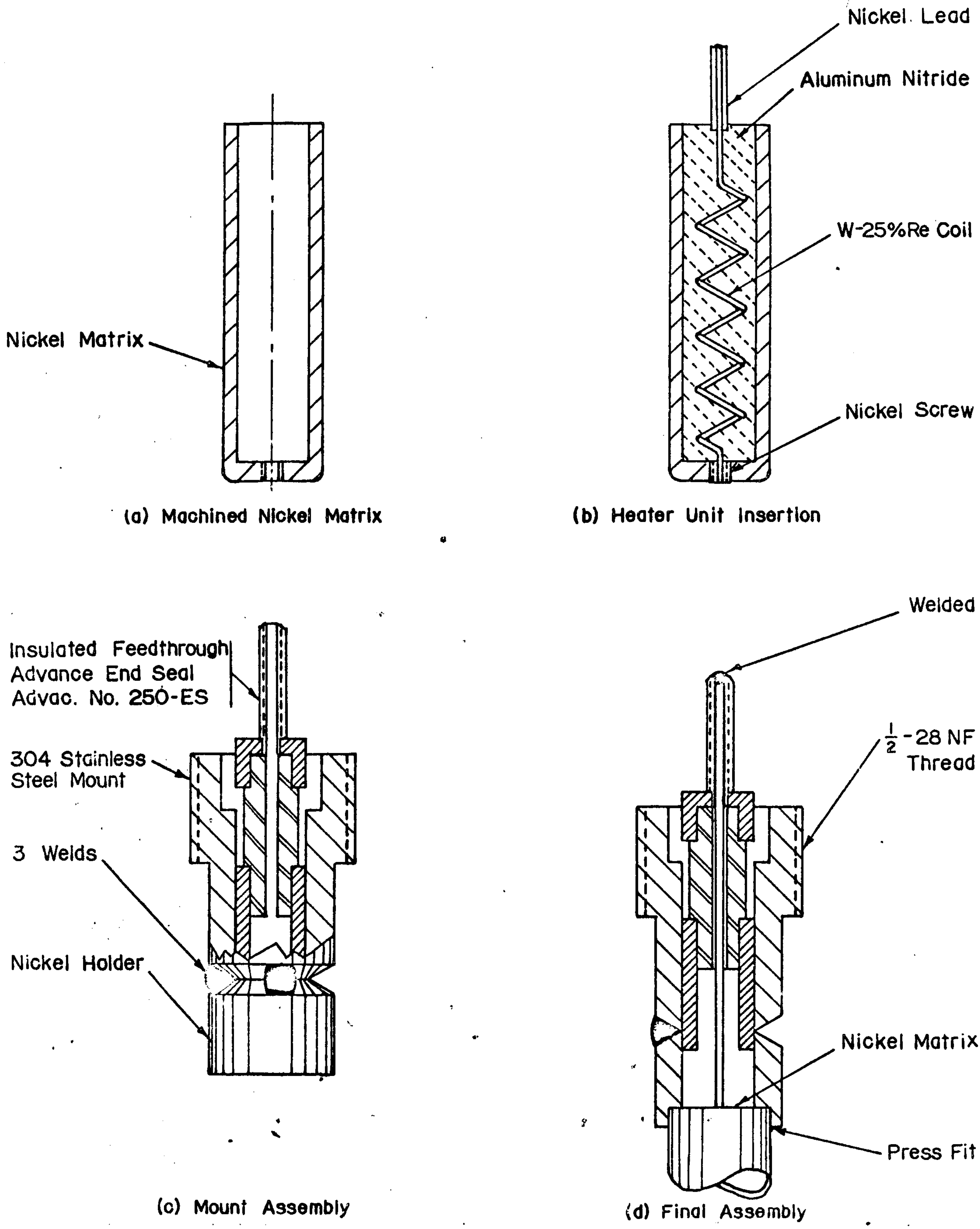


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FIG. 14 ASSEMBLY STEPS OF L.C.D. ENGINE CATHODE TYPE 3

TABLE 3. CATHODE LIFETIME STUDY - CONTRACT NO. NAS 3-3563

Page 1 of 1

## NICKEL POWDER PREPARATION DATA SHEET

| | |
|---|---|
| DATE: 8/10/63 MIXED BY: F.A. | Lot Number |
| APPROVED BY: [illegible] 8/21/63, H.B. 8/10/63 | B |

A. CARBONYL NICKEL POWDER:

To obtain 801 grams use triple beam balance.

Weight to be divided into 4 steps. As follows:

Approx. 200 grams of powder minus wt. of cont. = Wt. of powder

| | | | |
|---|---|---|---|
| Step #1 | 261.130 | - 60.240 | = 200.890 |
| Step #2 | 261.420 | - 60.245 | = 201.175 |
| Step #3 | 262.663 | - 60.248 | = 202.415 |
| | | Sub Total | 604.480 |
| Step #4 | 256.800 | - 60.250 | = 196.550 |
| | | TOTAL WEIGHT OF POWDER CHECK YOUR FIGURES | 801.030 |

B. RADIO MIX 3

To obtain 90 grams of RM3 use Sartorious balance

One step only:

| Wt. of Powder | Minus Wt. of Cont. | = | Wt. of powder |
|---|---|---|---|
| 150.2148 | - 60.2773 | = | 89.9975 |

C. ZIRCONIUM HYDRIDE

To obtain 9 grams of ZrH use Sartorious balance

| Wt. of Powder | Minus Wt. of Cont. | = | Wt. of Powder |
|---|---|---|---|
| 69.2772 | - 60.2771 | = | 9.0001 |

D. TOTALS:

| | | | |
|---|---|---|---|
| A. Wt. of Nickel Powder | = | 801.0300 | Grams |
| B. Wt. of Radio Mix 3 | = | 89.9975 | Grams |
| C. Wt. of Zirconium Hydride | = | 9.0001 | Grams |
| Total wt. of Powders | = | 900.0276 | Grams |

TABLE 4. CATHODE LIFETIME STUDY - CONTRACT NAS3-3563
FABRICATION DATA SHEET

- B

| PRE-SINTERING & POST-SINTERING INSPECTION DATA | | | | | ROUGH MACHINING INSPECTION DATA | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CATHODE NO | WGT. AFTER PRESS | WGT. AFTER SINTER | X-RAY RESULT | VISUAL | OUTSIDE DIA. TOP | OUTSIDE DIA. M.D. | OUTSIDE DIA. BOT. | CORE I.D. | OVER-ALL LGT. $L_1$ | CORE LGT. $L_2$ | CON-CENTRIC | WGT. | DENSITY * | VISUAL |
| ✓ 1-B | 27.8619 | 27.1895 | ✓ | ✓ | 4356 | .4350 | .4348 | .2510 | 1.0022 | .899 | .0003 | 11.7668 | 6.8671 | ✓ |
| ✓ 2-B | 28.7639 | 28.0746 | ✓ | ✓ | .4360 | .4358 | .4357 | .2510 | .9990 | .901 | .0004 | 11.7002 | 6.8380 | ✓ |
| ✓ 3-B | 28.4166 | 27.7368 | ✓ | ✓ | 4357 | .4352 | .4353 | .2513 | 1.0027 | .899 | .0001 | 11.7105 | 6.8298 | ✓ |
| 4-B | 28.5090 | 27.8133 | ✓ | ✓ | Not used because unmachined area large | | | | | | | | | |
| 5-B | 29.2078 | 28.4978 | ✓ | ✓ | " | " | " | " | " | " | | | | |
| 6-B | 29.3294 | 28.6233 | ✓ | ✓ | " | " | " | " | " | " | | | | |
| ✓ 7-B | 27.1022 | 26.9351 | ✓ | ✓ | .4352 | .4352 | .4352 | .2513 | 1.0025 | .900 | .0004 | 11.8830 | 6.9496 | ✓ |
| ✓ 8-B | 28.1122 | 27.4275 | ✓ | ✓ | 4356 | .4353 | .4353 | .2513 | 1.0014 | .899 | .0003 | 11.8958 | 6.8889 | ✓ |
| ✓ 9-B | 28.4546 | 27.7663 | ✓ | ✓ | 4349 | 4349 | 4354 | .2512 | 1.0021 | .901 | .0003 | 12.0620 | 7.0521 | ✓ |
| ✓ 10-B | 28.1920 | 27.4941 | ✓ | ✓ | 4346 | 4346 | 4355 | .2512 | .9997 | .9015 | .0002 | 11.6379 | 6.8559 | ✓ |
| ✓ 11-B | 28.7279 | 28.0232 | ✓ | ✓ | .4352 | 4352 | .4353 | .2515 | 1.0018 | .907 | .0002 | 11.9693 | 7.0304 | ✓ |
| ✓ 12-B | 27.7499 | 27.0724 | ✓ | ✓ | .4348 | .4347 | 4351 | .2512 | 1.0018 | .901 | .0003 | 11.9540 | 6.9824 | ✓ |
| ✓ 13-B | 27.6049 | 26.9221 | ✓ | ✓ | .4350 | 4350 | 4356 | .2513 | 1.0021 | .9005 | .0003 | 11.8583 | 6.9265 | ✓ |
| ✓ 14-B | 28.5127 | 27.8214 | ✓ | ✓ | .4351 | .4350 | 4348 | .2514 | 1.0018 | .900 | .0002 | 11.7635 | 6.8904 | ✓ |
| ✓ 15-B | 27.5488 | 26.8650 | ✓ | ✓ | .4350 | .4350 | 4354 | .2513 | 1.0020 | .905 | .0002 | 11.7859 | 6.9093 | ✓ |
| ✓ 16-B | 28.7546 | 28.0592 | ✓ | ✓ | .4356 | .4353 | .4353 | .2510 | 1.0020 | .900 | 0002 | 11.7352 | 6.8450 | ✓ |
| ✓ 17-B | 28.5936 | 27.9046 | ✓ | ✓ | .4350 | 4352 | 4356 | .2510 | .9997 | .902 | .0003 | 11.6904 | 6.8473 | See Note ✓ |
| ✓ 18-B | 28.5554 | 27.8594 | ✓ | ✓ | .4350 | .4353 | .4355 | .2510 | 1.0019 | .900 | .0003 | 11.9671 | 6.9811 | |
| 19-B | 28.5432 | 27.7657 | rejected diff [illegible] | | | | | | | | | | | |
| ✓ 20-B | 28.4197 | 27.7276 | ✓ | ✓ | 4358 | .4353 | 4345 | .2510 | 1.0025 | .899 | .0004 | 11.8931 | 6.9088 | ✓ [illegible] |
| ✓ 21-B | 28.2455 | 27.5637 | ✓ | ✓ | 4349 | .4348 | .4357 | .2515 | 1.0010 | .900 | .0003 | 11.6932 | 6.8529 | ✓ |
| ✓ 22-B | 28.5715 | 27.8803 | ✓ | ✓ | .4346 | 4346 | .4354 | .2511 | 1.0024 | .901 | .0002 | 11.7784 | 6.8835 | See Note |
| ✓ 23 B | 28.5163 | 27.8259 | ✓ | ✓ | .4350 | 4348 | .4352 | .2518 | 1.0007 | .901 | .0002 | 11.8271 | 6.9501 | ✓ |
| ✓ 24 B | 28.4643 | 27.7766 | ✓ | ✓ | .4356 | .4356 | .4347 | .2513 | 9984 | .9033 | .0003 | 11.7907 | 6.9332 | ✓ |
| ✓ 25 B | 28.0401 | 27.3506 | ✓ | ✓ | .4357 | .4355 | .4348 | .2510 | 1.0018 | .899 | .0003 | 11.8921 | 6.9349 | ✓ |
| 26 B | 29.0433 | 28.3388 | ✓ | ✓ | .4345 | 4345 | .4360 | .2512 | 1.0020 | .900 | .0004 | 11.9067 | 6.9004 | ✓ |
| 27 B | 28.2007 | 27.5188 | ✓ | ✓ | .4355 | .4355 | .4348 | .2510 | 1.0010 | .900 | .0008 | 11.8081 | 6.9154 | ✓ |
| 28 B | 28.9574 | 28.2620 | ✓ | ✓ | .4349 | .4349 | .4356 | .2511 | 1.0019 | .900 | .0003 | 11.8582 | 6.9224 | ✓ |
| Insp'd By: | W.F.S. | G.T.S. | G.T.S. | G.T.S. | A.R. on machined dimensions, W.S. on wgt. D. [illegible] | | | | | P. E. App. [illegible] 11/22/63 | | | | |
| Date: | 10/1/63 | 10/1/63 | 10/1/63 | 10/1/63 | 10/17/63 | | | | 10/31/63 | Q. C. App. DR 11/22/63 | | | | |

* Density Formula:

$$D = \frac{Wt.}{\pi\left(\frac{\text{Avg. O.D.}}{2}\right)^2 L_1 - \pi\left(\frac{\text{I.D.}}{2}\right)^2 L_2}$$

gms/cm$^3$

Notes:

Visual

The exterior surface of 17 B & 22 B could not be uniformly turned down to .435. Near the .250 opening, both cathodes have an unmachined area, as shown below in 2 views.

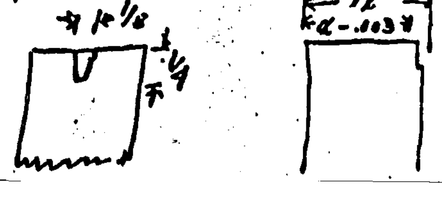


TABLE 5. CATHODE LIFETIME STUDY - CONTRACT NO. NAS3-3563

ASSEMBLY DATA SHEET

Lot Number - 13

| Cathode Number | Cold Resistance R1 * | R2 * | R3 * | R4 * | Outside Diameter Top | Mid. | Bott. | X-ray | Visual | Component Part Numbers FIL. B-16020 | ATT. SCR B-16016 | FIL. LEAD B-16019 | CATH. HOLDER B-5103 | BODY HOLDER B-5104 | INS. B-16021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| * 1B | .176 | .174 | .176 | .179 | .3118 * | .3118 | .3118 | OK | ✓ | 58 | 81 | 11 | 97 | 163 | 130 |
| 2B | .176 | .176 | .179 | .174 | .3118 | .3118 | .3118 | OK | ✓ | 61 | 56 | 19 | 69 | 113 | SAME 110 |
| 3B | .174 | .176 | .174 | .176 | .3117 | .3117 | .3117 | OK | ✓ | 59 | 67 | 57 | 10 | 60 | 159 |
| 7B | .173 | Reject | oil | soaked | | | | | | 70 | 100 | | | | |
| 8B | .176 | .174 | .179 | .179 | .3113 | .3116 | .3116 | OK | ✓ | 69 | 102 | 59 | 123 | 41 | 48 |
| * 9B | .176 | .174 | * | H.I.D | | | | | | 66 | 90 | | | | |
| 10B | .174 | .176 | .179 | .179 | .3117 | .3117 | .3117 | OK | ✓ | 60 | 63 | 60 | 88 | 110 | 82 |
| 11B | .174 | .172 | .174 | .174 | .3116 | .3116 | .3116 | OK | ✓ | 67 | 105 | 61 | 157 | 105 | 77 |
| 12B | .172 | .168 | .174 | .176 | .3116 | .3116 | .3116 | OK | ✓ | 62 | 53 | 62 | 171 | 20 | 171 |
| 13B | .176 | .176 | .179 | .176 | .3118 | .3118 | .3119 | OK | ✓ | 63 | 51 | 63 | 161 | 160 | 142 |
| 14B | .175 | Reject | oil | soaked | | | | | | 72 | 57 | | | | |
| 15B | .174 | .172 | .179 | .179 | .3118 | .3117 | .3117 | OK | ✓ | 74 | 4 | 64 | 115 | 178 | 44 |
| 16B | .172 | .174 | .181? | .176 | .3118 | .3119 | .3119 | OK | ✓ | 65 | 88 | 68 | 180 | 130 | 115 |
| 17B | .174 | .176 | .179 | .179 | .3118 | .3118 | .3116 | OK | ✓ | 85 | 117 | 66 | 126 | 26 | 35 |
| 18B | .176 | .174 | .174 | .176 | .3118 | .3118 | .3118 | OK | ✓ | 64 | 86 | 67 | 52 | 68 | 6 |
| 20B | .174 | .174 | .178 | .179 | .3118 | .3117 | .3118 | OK | ✓ | 86 | 116 | 68 | 91 | 65 | 1 |
| 21B | .175 | .176 | .176 | .179 | .3118 | .3117 | .3118 | OK | ✓ | 87 | 115 | 69 | 60 | 156 | 112 |
| 22B | .175 | .175 | .177 | .176 | .3117 | .3117 | .3116 | OK | ✓ | 77 | 114 | 70 | 93? | 57 | 196 |
| 23B | .174 | .174 | .179 | .179 | .3117 | .3118 | .3117 | OK | ✓ | 89 | 118 | 71 | 62 | 172 | 145 |
| 24B | .174 | .176 | .176 | .176 | .3110 | 3110 | .3117 | OK | ✓ | 78 | 119 | 72 | 124 | 2 | 101 |
| 25B | .175 | .174 | .176 | .176 | .3118 | .3118 | .3118 | OK | ✓ | 81 | 120 | 73 | 65 | 112 | 100 |
| 26B | .174 | .174 | .174 | .174 | .3117 | .3118 | .3117 | OK | ✓ | 82 | 121 | 74 | 194 | 29 | 90 |
| 27B | .179 | .176 | .174 | .179 | .3118 | .3117 | .3117 | OK | ✓ | 84 | 123 | 75 | 141 | 140 | 133 |
| 28B | .175 | .173 | .176 | .176 | .3102 | .3104 | .3117 | OK | ✓ | 88 | 124 | 76 | 172 | 162 | 166 |
| Insp'd By: | B.G. | B.G. | B.G. | B/G | AK | | | MRS | M. | P.E. App. W.S. 12/19 | | | | | |
| Date | 12/10 | 12/11 | 12/16 | 12/16 | 12/4 | | | 12/11 | 12/15 | Q.C. App. RR. 12/19 | | | | | |

* $R_1$ - Filament Resistance

$R_2$ - Fil., Screw & AlN Resistance

$R_3$ - Fil., Screw & AlN & Lead Resistance

$R_4$ - Resistance of Completed Assembly

Remarks:

*MARK ON SURFACE

*Bubble in aluminum nitride

this figure. An appreciation of the effort involved can be gained by noting the many operations and subsequent expenditures of time required in the fabrication of one lot as detailed in Table 6.

That only 5 of the 7 scheduled lots were completed at the program's end could only be partly attributed to the increased fabrication time. Serious delays were encountered in the manufacture and delivery of the filament used in the cathode heater element. The filaments, which were formed by a local supplier were initially delivered a month and a half late. Incoming inspection showed that the filaments were not made to specifications. Thirty-two threads per inch of wire were formed instead of the twenty-four threads per inch that were called out in the drawing (Fig. 15). In addition, the coaxial legs were bent to such an extent that "as is" a filament could not be axially mounted in a cathode. The shipment, with the exception of 24 filaments, was returned to the vendor. The legs of the 24 were straightened in-house and inserted into the cathodes of the parametric study. The supplier finally completed the order by purchasing new wire and forming it to the proper specifications. This required an additional 2 months. Consequently, the fabrication of the first test lot was not completed until two months after the date originally scheduled.

## 4.2 CONDITIONING SCHEDULE

The conditioning of the nickel matrix cathodes was terminated by an evaluation of the operating characteristics of the cathodes in a hard vacuum ($10^{-6}$ torr) under controlled conditions. The purpose of the evaluation was to determine how similar or dissimilar, as the case may be, cathodes of a test lot were to each other or to cathodes of another test lot.

Conditioning was conducted in the Conditioning Test System which is described in Section 3.1. One-half of a test lot (12 cathodes) were processed simultaneously. The conditioning schedule was divided into 3 parts. In the

Table 6  Effort Involved in Fabricating One Test Lot

| Task | Description of Task | Operator | Hours to Complete |
|---|---|---|---|
| 1 | Sterilize powder containers and measuring utensils | Technician | 1 |
| 2 | Weigh powders, mix, clean area, set tumbling | " | 2 |
| 3 | Form (28) latex tube containers | " | 1.5 |
| 4 | Sterilize tubes, stoppers and powder containers | " | 1.5 |
| 5 | Distribute tumbled powders equally into (28) powder containers, clean area | " | 3.5 |
| 6 | Pack (28) tubes, number, clean area | " | 22 |
| 7 | Prepare pressing area and apparatus, press (28) slugs, clean area | " | 6 |
| 8 | Strip, mark and weigh (28) slugs | " | 3 |
| 9 | Sinter (28) slugs | " | 4 |
| 10 | Radiograph (28) slugs | " | 3 |
| 11 | Weigh (28) slugs | " | 1 |
| 12 | Machine (28) slugs to solid cylinders, inspect | Machinist | 28 |
| 13 | Machine (24) cylinders to canisters, match screws to threaded hole, inspect | " | 25 |
| 14 | Weigh (24) cathodes | Technician | 1 |
| 15 | Calculate densities of (24) cathodes | " | 1 |
| 16 | Measure filament resistance and align in cathode (24) | " | 3 |
| 17 | Pack aluminum nitride powder into (24) cathodes | " | 12 |
| 18 | Radiograph (24) cathodes | " | 3 |
| 19 | Form (24) latex tube containers | " | 1.5 |
| 20 | Crimp filament to screw (24) | " | 0.5 |
| 21 | Prepare pressing area and apparatus, press (24) units, clean area | " | 5.5 |
| 22 | Strip and measure resistance | " | 2 |
| 23 | Machine to final dimensions (24) and match to holder, inspect | Machinist | 21 |
| 24 | Crimp filament to lead (24) and measure resistance | Technician | 2 |
| 25 | Press cathode to mount and weld | Machinist | 5 |
| 26 | Measure resistance (24) | Technician | 1 |
| 27 | Radiograph finished cathodes (24) | " | 3 |
| | | | 163 |
| 28 | Supervision | Project Leader | 10 |
| 29 | Supervision | Quality Control Officer | 20 |
| | TOTAL TIME--- | | 193 |

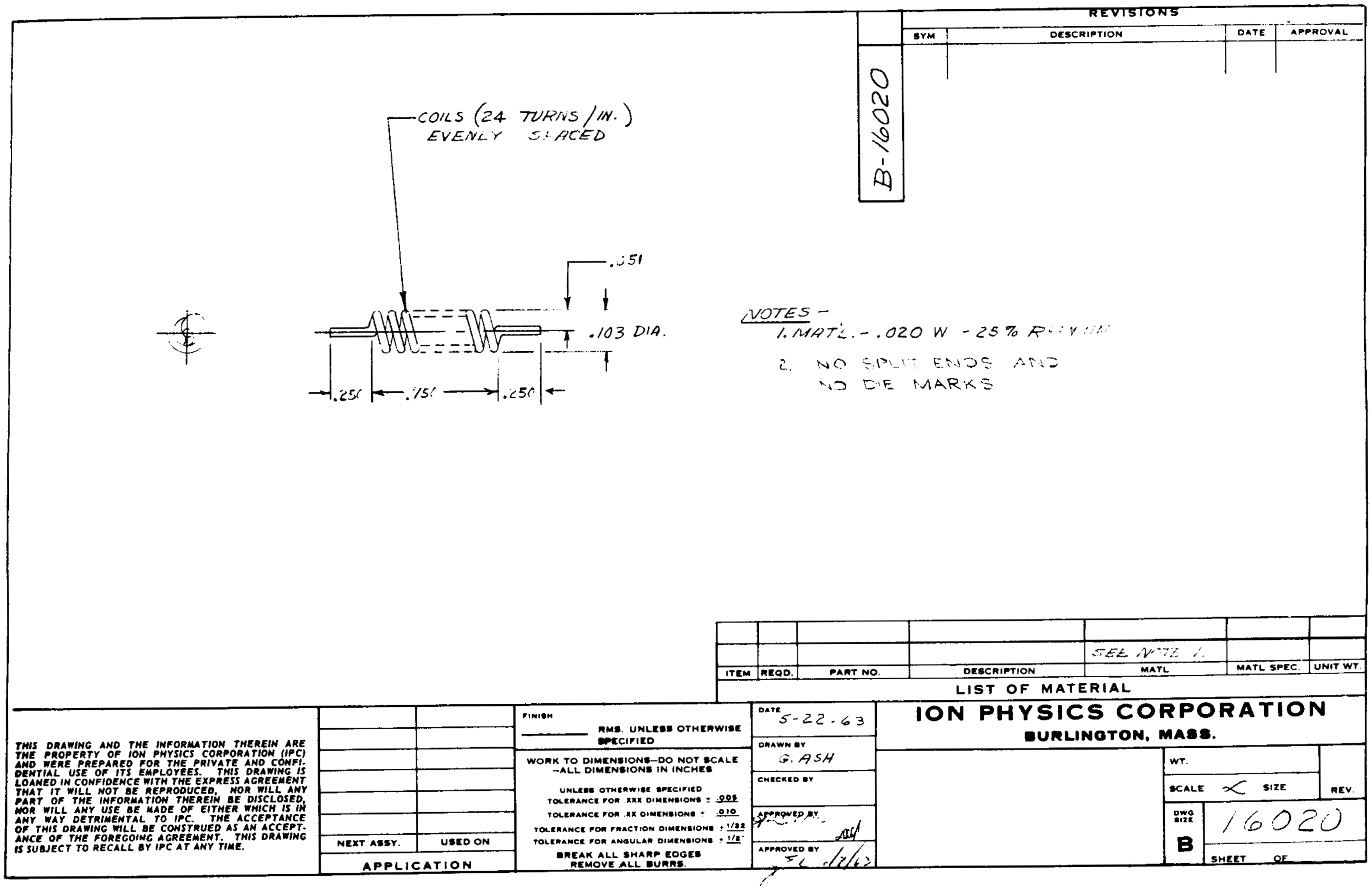



FIG. 15-FILAMENT AS USED IN THE LOW CURRENT DENSITY ENGINE CATHODE TYPE 3

first part, the cathodes were gradually brought to temperatures above 1000°C, held there for one hour, and then returned to ambient temperatures, and subsequently, opened to the atmosphere. The object of this phase was to ensure that the alkaline-earth carbonates were completely reduced to their oxides. The major outgassing of all cathode components was also accomplished. The second part is similar to the first in that the cathodes were again brought to temperatures above 1000°C. However, the cathodes were now enclosed by cylindrical anodes. At the elevated temperatures, the emission characteristics of each cathode were measured. After these measurements were taken, the 12 diodes were run in parallel at a fixed d.c. potential for approximately 16 hours. At the close of this period, the third part began and it consisted mainly of emission characteristic measurements at various temperatures. The conditioning schedule in its entirety is shown in Appendix B.

The results of all the conditioning tests showed that:

(1) there was no significant difference between any of the cathodes tested with respect to heater characteristics;

(2) for any given cathode surface temperature, each cathode would require essentially the same heater power; i.e., no significant variation in insulator conductivity or surface emissivity;

(3) the initial outgassing operation effectively removed or eliminated the great bulk of occluded gases. The second heat-up exhibited only slight evidence of outgassing; and

(4) within any particular lot, cathode emission behavior was essentially uniform. However, when all the lots were compared, it could be seen that the emission characteristics varied from lot to lot (Fig. 16). Although this behavior first suggested a fabrication problem, possibly in sintering, the fact that the level of emission also dropped with the order in which the lots were tested indicates that the problem may be one connected with the conditioning schedule or system. Early in the program, some difficulty was experienced with oil backstreaming. This happened before any of the test lots were conditioned. A refrigerated baffle was installed in order to eliminate this backstreaming.

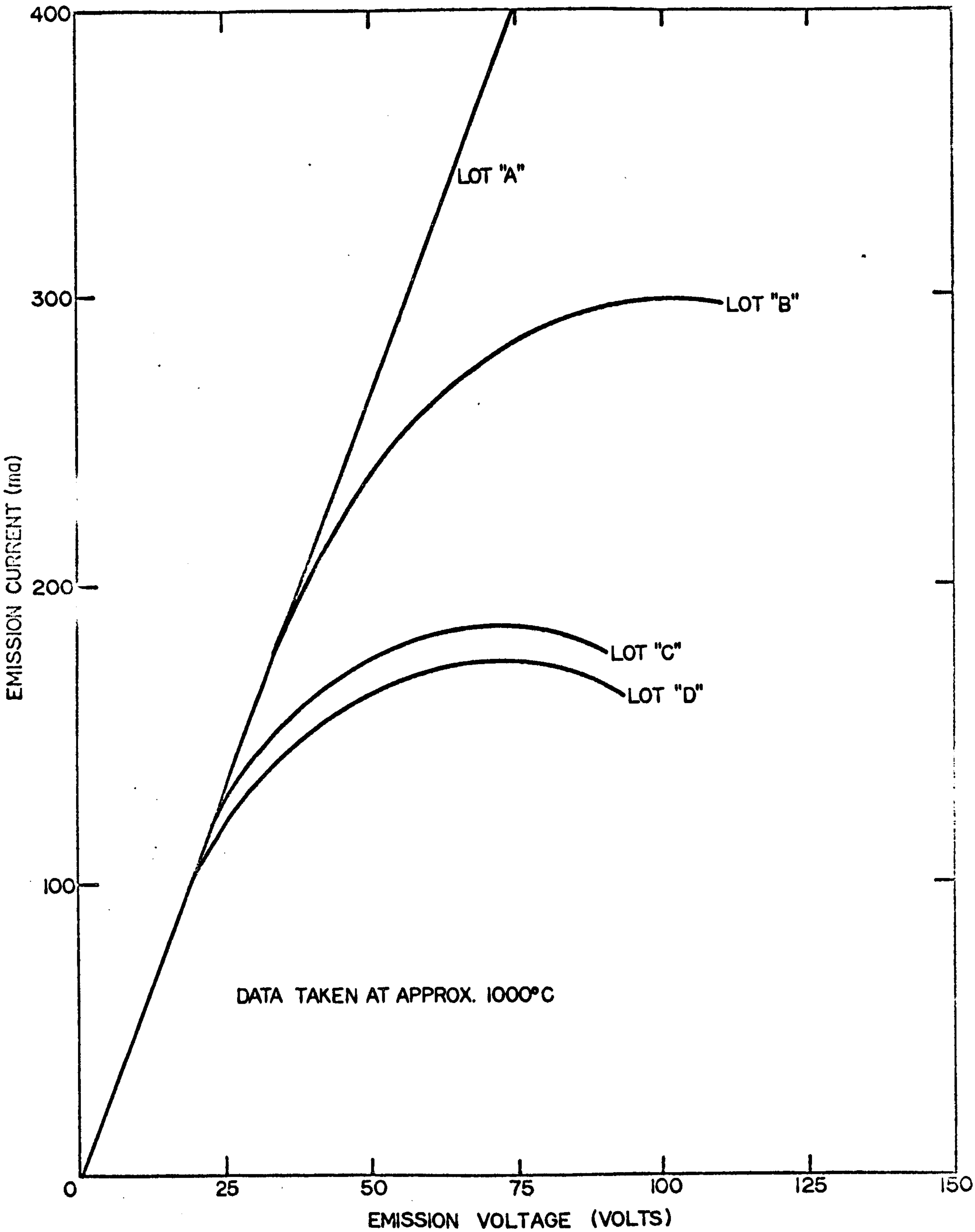



FIG. 16 AVERAGE EMISSION OF CATHODE LOTS
(CONDITIONING TEST SYSTEM)

1-864

It is now questionable whether or not this arrangement was effective. There is an indication, which is unsubstantiated, that emission is greater in a cathode that has been conditioned in a system that employs a mercury diffusion pump. In any event, these variations (in effective work function of the emitter) appear to be eliminated with ion bombardment conditioning of the surface and hence may be just confined to vacuum operation.

As will be noted in Section 6, the arc behavior of the cathodes revealed no significant differences.

# 5. HEATER LIFETIME TESTS

## 5.1 EXPERIMENTAL RESULTS

The purpose of the heater lifetime tests was to determine the reliability of the cathode filament through temperature cycling tests conducted under accelerated conditions in a hard vacuum ($10^{-6}$) environment. Thirty-six cathodes, selected from the 6 test lots and grouped in lots of 12, were to be temperature cycled in 3 separate but identical tests as detailed in Tables 1 and 2. The tests were conducted in the heater test system which is described in Section 3.1.

The outline of the test was as follows. The test system was first brought into the $10^{-6}$ torr region. The temperatures of the 12 cathodes were then stabilized at 1000°C and the control variac for each heater power supply was "locked." Next, an automatically-cycled circuit breaker in the power supply line was activated (Fig. 5). The device was programmed for a continuous 4-minute power cycle: 2 1/2 minutes with power off, 1 1/2 minutes with full power on. The time position of the power cycle was then adjusted until the beginning, and consequently the end, of each cycle coincided with a cathode temperature of approximately 900°C. Thus, at the instant power was simultaneously removed from each cathode heater, the surfaces of the cathodes were at 900°C. During this phase of the cycle, the temperatures of the cathodes slowly decreased until at the end of the 2 1/2 minute period, temperatures of about 500°C were reached which corresponded to a "standby" condition for which only 15% of the operating power is required. Simultaneously, to each heater and within 1 1/2 minutes, the temperatures rose to 900°C at which point the cycle was repeated. The test was to continue in this manner for approximately 2 1/2 months in which time a possible total of 25,000 temperature cycles per cathode could be achieved.

Only one of the 3 scheduled tests was initiated and completed. Test lots were not available until January for reasons already discussed.

On January 3, 12 cathodes, 6 from lot A and 6 from lot B, were placed in cyclic operation. On February 24, the test was interrupted by the failure of the automatic circuit breaker. During the period while a replacement was enroute, unrepairable cathode heater failures were replaced by cathodes from lots C and D. Structural defects that caused the failure of several other cathodes were corrected, and the cathodes were returned to the test. The test resumed on February 28 and continued without incident until it was terminated on March 30.

The summation of the test results is listed in Table 7 and is shown graphically in Fig. 17. It is seen that 18 cathodes were employed in the test. Of this number 14 experienced catastrophic filament failure before termination of the test. Three cathodes also experienced mechanical failures which were repairable. These were Class 1 failures. The final cathode assembly step or stage involved welding the nickel extension lead to the metal portion of the ceramic insulator (Fig. 14). In the case of the three Class 1 failures, this weld broke under repeated temperature cycling. This condition for both these cathodes and those following in fabrication, was corrected by increasing the power applied during welding and increasing the contact surface area of the weld. As all 3 had failed in test A, once repaired, the cathodes were put into operation in test B. As noted in Table 4, the test letters respectively signify the test periods before and after the system malfunction and the subsequent interruption.

Table 7. Test Results of the Temperature Cycling Life Test Detailing Number of Temperature Cycles Attained Before Either Test Termination or Unit Failure

| Cathode Number | Test Part* | Class of Failure* | | Number of Temperature Cycles: Minimum | Maximum | Mean |
|---|---|---|---|---|---|---|
| 16B | A | 3 | | 30 | 240 | 135 |
| 13A | A | 1 | | 240 | 660 | 450 |
| | B | 2 | | 3, 420 | 3, 780 | 3, 600 |
| 14A | A | 1 | | 240 | 660 | 450 |
| | B | 3 | | 4, 140 | 5, 220 | 4, 680 |
| 15B | A | 3 | | 2, 400 | 3, 480 | 2, 940 |
| 10A | A | 1 | | 4, 560 | 4, 920 | 4, 740 |
| | B | none | | 9, 500 | 9, 500 | 9, 500 |
| 17C | B | 2 | | 7, 020 | 7, 380 | 7, 200 |
| 21C | B | 2 | | 7, 380 | 7, 740 | 7, 560 |
| 1D | B | none | | 9, 500 | 9, 500 | 9, 500 |
| 2D | B | none | | 9, 500 | 9, 500 | 9, 500 |
| 4D | B | none | | 9, 500 | 9, 500 | 9, 500 |
| 21A | A | 3 | | 10, 320 | 10, 680 | 10, 500 |
| 15A | A | 3 | | 10, 680 | 11, 040 | 10, 860 |
| 13B | A | 2 | | 17, 160 | 18, 600 | 17, 880 |
| 17B | A | 2 | | 17, 160 | 18, 600 | 17, 880 |
| 20B | A | none | | 18, 600 | 18, 600 | 18, 600 |
| | B | 2 | | 4, 140 | 5, 220 | 4, 680 |
| 10B | A | none | | 18, 600 | 18, 600 | 18, 600 |
| | B | 2 | | 5, 220 | 5, 580 | 5, 400 |
| 12A | A | none | | 18, 600 | 18, 600 | 18, 600 |
| | B | 3 | | 6, 315 | 6, 660 | 6, 488 |
| 18C | B | 2 | | 4, 140 | 5, 220 | 4, 680 |
| | | | Total | 208, 300 | 199, 245 | 203, 820 |

*See Text for Explanation

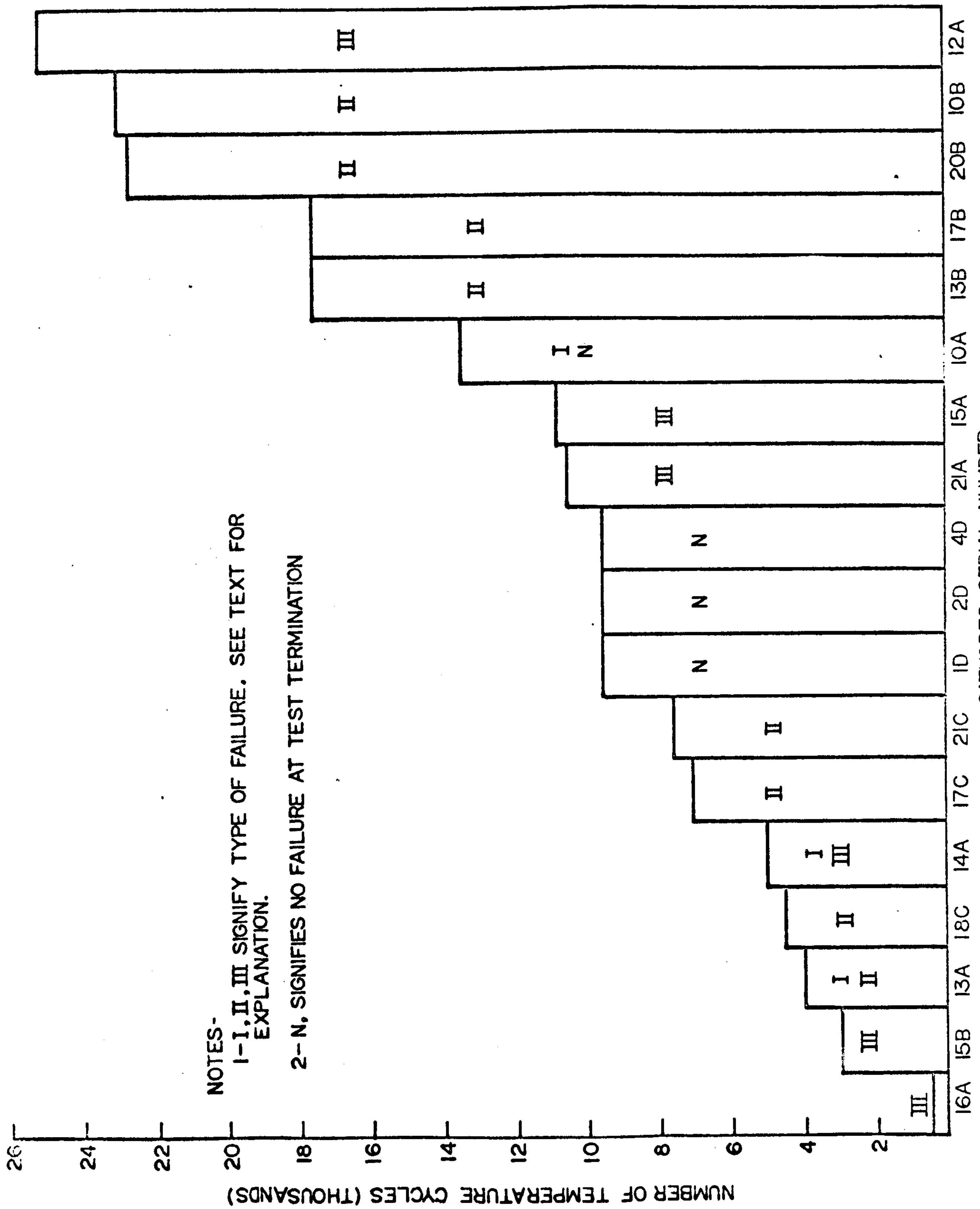



FIG. 17 TEMPERATURE CYCLE TEST DATA



I-867

Eight cathodes were Class 2 failures in which the cause of failure was a burned-out filament. The means by which the filaments burned-out involved three sequential and interdependent structural changes, namely:

(1) At some point of time in the cycling test, the aluminum nitride powder in the immediate vicinity of the filament began to sinter - going from a compressible powder-like state to that of a ceramic state.

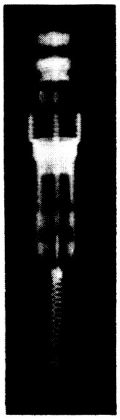
(2) During each cycle the coils of the filament expanded and contracted within the sintered nitride. Before the insulating powder was thoroughly sintered into a hard ceramic form, the coils were able to move with little hindrance through the powdered mass. Also, during the cycling the spacing between individual coils remained fairly constant. However, as the powder began to sinter, rigid ceramic ridges began to form between some of the coils. As these ridges widen, the spacing between coils became correspondingly smaller.

(3) As the ceramic ridges were forming, less and less of the filament's surface was coming in contact with the aluminum nitride. Thus, the filament temperature increased, and, in turn, each coil attempted to traverse a larger distance

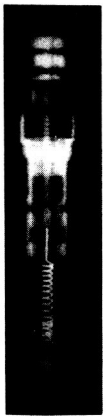
Eventually, during the cycling, two or more coils would come in contact with one another, and in some cases would fuse together. Then, the subsequent reduction in series resistance at a fixed voltage drop would raise the filament current which, in turn, increased the filament temperature.

For most of the "on" phase of the cycle, 10 amperes at 6 volts were passed through the heater units of the cathodes. However, for the first few seconds, the filaments were subjected to currents of 13.5 amperes at 6.5 volts. It was most likely that during this period the filaments, already at a higher than normal temperature, burned-out under the increased current load. Radiographs of several of these failures are shown in Fig. 18. The burnouts always occur just above the first coil as this was the hottest area.

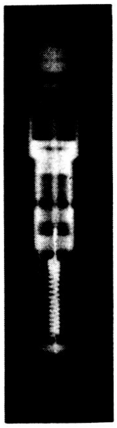
Six cathodes were Class 3 failures. Like the previous class, the failures involved opened filaments. However, there the similarity ended.



CATHODE No. 18C



CATHODE No. 17B



CATHODE No. 21C

FIG. 18 RADIOGRAPHS OF THREE CLASS II TEMPERATURE CYCLING TEST FAILURES

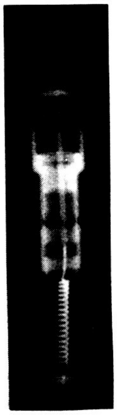
I-745

The breaks were caused by fractures and not by burnouts. Radiographs of several of these failures are shown in Fig. 19. It can be noticed that there is little distortion in the coils and that each break is at or above the first coil. Although both coaxial legs were subjected to the same stresses in fabrication, the upper was in a higher temperature regime, hence, experienced greater thermal stresses. The attachment to the nickel extension lead also imposed a stress burden on the upper leg.

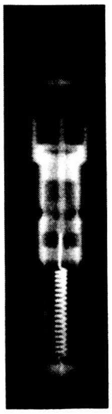
Neither Class 2 nor Class 3 failures were gradual with respect to exterior operating conditions. Temperatures and power measurements for each cathode remained substantially unchanged throughout the test.

## 5.2 CONCLUSION

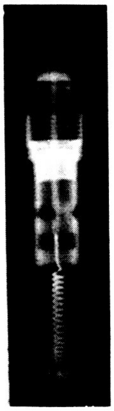
From Table 4 it is shown that the cathodes accumulated a mean total of 200,000 temperature cycles. Using an authoritative source,[6] a statistical reliability analysis was made of the manner by which this total was reached. The results of this analysis are illustrated in Fig. 20. The curves show what levels of confidence and reliability are predicted for numbers of temperature cycles up to a figure of 5000 cycles. Thus, for example, the tests demonstrated that for 50% of the time it would be possible that out of 1000 cathodes placed in cyclic operation 980 could perform 5000 cycles without failure. Under the same conditions but at a 95% confidence level, only 916 cathodes would reach 5000 cycles without failure. Even at a reduced mission life of 1000 cycles, the percentage of failures at high confidence levels would exceed 1%. Hence, the indications are that from a statistical standpoint the cathode, with the present heater design, would be too unreliable for any type of ion engine operation. Furthermore, it has become increasingly more evident that the intrinsic faults of any heater design, based upon a filament embedded in another material, are such that it is believed that no amount of modification will increase the reliability figures of this type of unit to acceptable levels.



CATHODE No. 15B



CATHODE No. 16B



CATHODE No. 21A

FIG. 19 RADIOGRAPHS OF THREE CLASS III TEMPERATURE CYCLING TEST FAILURES

1-746

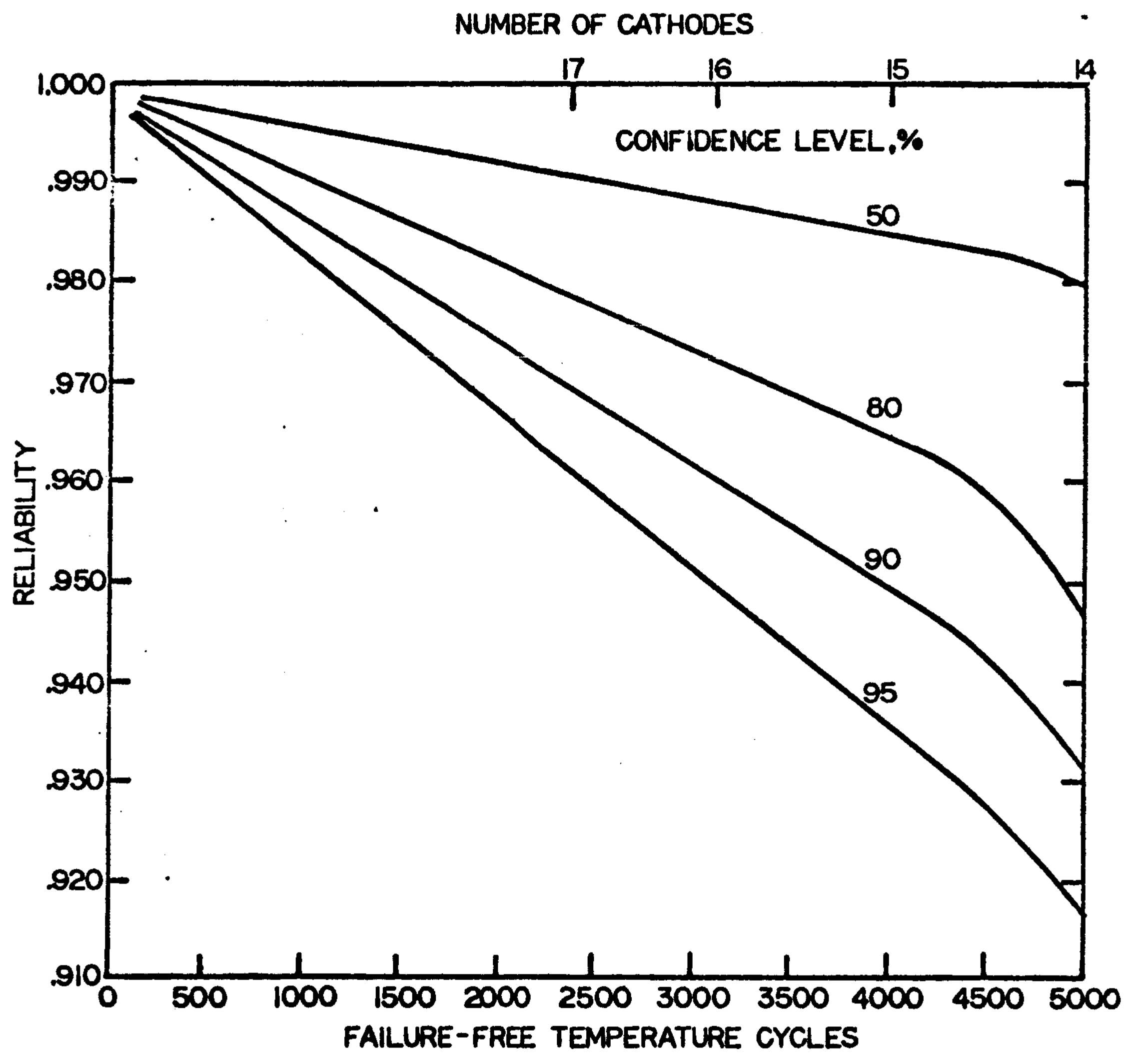



FIG. 20 RELIABILITY VALUES ATTAINED IN THE TEMPERATURE CYCLING TEST

# 6. MERCURY LIFE TESTS

## 6.1 EXPERIMENTAL RESULTS

The purpose of the mercury life tests was to evaluate the emitting characteristics of the nickel matrix cathodes in the mercury arc environments of 12 simulated electron-bombardment-type ion engines. The tests that the cathodes were to participate in were basically of two types. The first type was the continuous d.c. operation test. In this test, 12 cathodes at temperatures of about 950°C were to simultaneously sustain 12 individual mercury arcs for extended periods. Arcs operating at a 4-ampere emission level at potentials of 50 volts were to be maintained for 200 hours for 3 runs, and for 2000 hours for a fourth run. The second type of test was the interrupted d.c. operation test. As in the previous tests, 12 cathodes were to simultaneously sustain 12 individual mercury arcs. However, during each normal working day, the arcs were to be extinguished and the cathodes were to be cycled from operating temperature to ambient temperature and back to operating temperature. This was to happen three times per day. These tests, which numbered three, were to be terminated when a total of 200-arc hours per cathode were accumulated. The proposed test schedule and the selection of test cathodes are detailed in Tables 1 and 2.

The lifetime tests were never conducted in an entirely satisfactory manner due to a number of system difficulties revealed in the parametric studies. Initially, cathode fabrication problems and late delivery of the mercury test system parts delayed the start of the parametric studies by 3 1/2 months. The studies were intended to serve as a means for determining operating procedures and also to uncover any system conditions that required modifications. As scheduled, the studies were to require less than a month's effort and were to involve 12 cathodes. In fact, the studies covered a period of 3 1/2 months, and some 49 cathodes were employed in the experiments. A good portion of the delay was due to the fact that the studies did require more effort than was initially anticipated. A number of modifications had to be made before an adequate delineation of the environmental test conditions could be acquired. Chief among them was a complete revision of the mercury feed system, the details of which have been discussed in Section 3. 2. The time involved and the number of test cathodes were also considerably increased by vacuum problems. In an early test, high interior wall temperatures caused considerable outgassing of the Edwards vacuum rotary seals. The resulting hydrocarbon vapor contaminated the cathodes under test. This condition was corrected by adding additional exterior cooling coils and by a thorough cleaning of the seals. Vacuum leaks also caused several tests to be abruptly halted. During two tests, an electrical feedthrough broke breaking the vacuum, while during two other tests, welds in the water shield fractured also breaking the vacuum. Once the studies were concluded, 12 new cathodes were placed in arc operation. However, vacuum leaks were again responsible for an early test termination. Moreover, the leaks could not be repaired so that entirely satisfactory continuous operation of the system was not accomplished for a period of more than 100 hours.

While the specifications of the mercury life tests were not completely fulfilled, 7000 hours of mercury arc operation accomplished by 61 cathodes generated a number of results namely:

(1) Each of the 61 cathodes operated for an extended period in the low-voltage mercury discharge. In general, a d.c. potential of between 15 and 20 volts applied simultaneously to the 12 cathodes was required to initiate mercury arcs as in normal engine operation. Ignition of the 12 arcs was accomplished within a minute of startup and was random with respect to the order in which the "engines" were activated.

(2) At approximately the same temperatures and at any one given time, the difference between the maximum and minimum arc currents being sustained by the 12 cathodes was always less than 10% of the maximum arc current present. It was also noted that the variance between cathode heater powers for any given temperature was negligible. The normal operating cathode temperature was 950°C. In the beginning when the cathodes were installed in the central support plate, heater powers of 90 watts and greater were needed to maintain the correct temperature level. The mounting arrangement was modified to that as shown in Fig. 21. This brought the heater power down to an average level of 60 watts (9.5 amperes at 6.2 volts).

(3) The arcs always acted in a collective manner. The currents together would increase and decrease by the same amounts. At first this action was thought to be caused by plasma coupling between individual engines. Investigation showed that plasma coupling did exist. Each engine was then electrostatically isolated from its neighbor by extending each outer heat shield until they were in contact with the surface of the cryopanel. Stainless steel mesh was used for the extension material. Arc operation after the modification was effected showed that the arcs still acted as a group.

(4) No arc current decay that could be attributed to emitter degradation was ever noted. As discussed above, the arcs acted in unison. If the arc current of one cathode decreased from a 5-ampere operating level, its performance was normally duplicated by the other cathodes. The longest continuous arc run lasted for 198 hours at an average arc current of 2 amperes at 25 volts.

Besides the data accrued in the mercury arc environments, post-run, hard vacuum emission tests were conducted on several of the cathodes that had sustained mercury arcs for periods of 50 to 100 hours. The results were compared with the original conditioning data and are shown in Fig. 22. It is significant that the indication is that the emitting properties have been enhanced somewhat through arc operation.

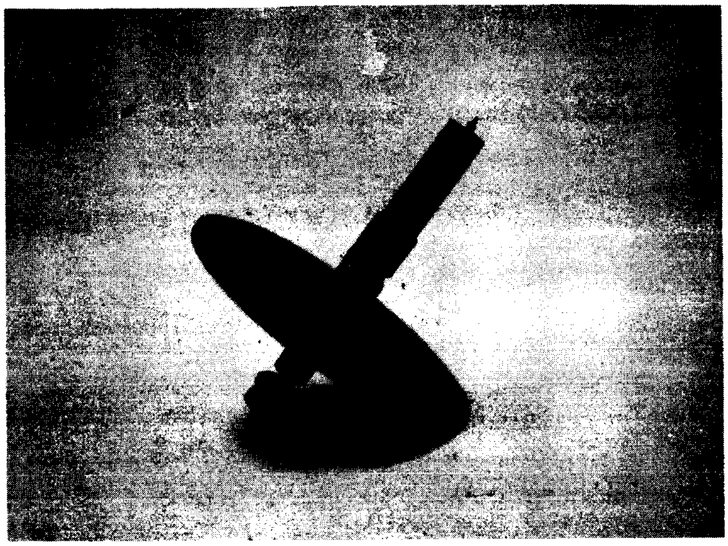


FIG. 21 VIEW OF A CATHODE INSTALLED IN THE MOUNTING PLATE OF A SIMULATED LOW CURRENT DENSITY ION ENGINE

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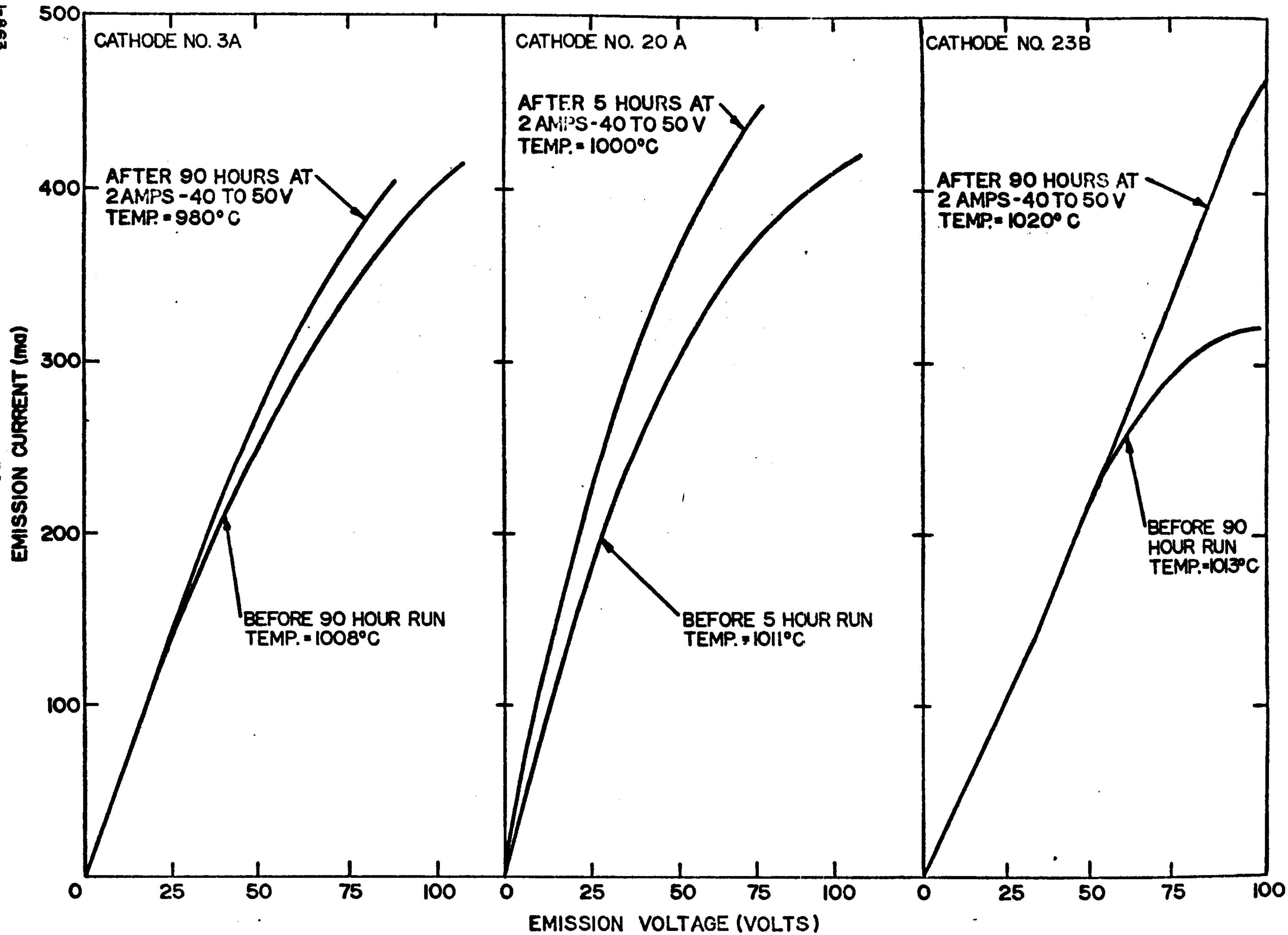


FIG. 22 EMISSION DATA OF THREE MERCURY LIFETEST CATHODES

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## 6.2 CONCLUSIONS

(1) The coiled heater configuration is considered unsatisfactory for a cathode used ion engine applications.

(2) The impregnated nickel matrix is compatible in all respects with operation in a Kaufman-type bombardment thrustor fed with mercury vapor although, as of yet, thousands of hours of operation with this type of cathode has not been realized in an engine.

(3) The sputtering losses of the cathode at 50 volts arc drop in the simulated engine are negligible and are compatible with at least one year's continuous operation in such an environment.

(4) The monolithic heater geometry developed during the course of this effort under IPC support can lead to a cathode unit capable of the high reliability and confidence demanded by the application.

(5) The present cathode mix, fabrication, and machining techniques are considered to be sufficiently well controlled and reproducible to serve as a "standard" matrix for further development work.

# 7. SUMMARY CONCLUSIONS

The objectives of the program were only met in part. Reliability and confidence figures were obtained for the heater element. These figures, and the failure analysis, necessitate the judgment that the present heater unit is unsuitable for ion engine applications. The lack of adequate mercury pressure control precluded proper environmental conditions under which the mode of existence and the mechanics of arc current decay could be evaluated. It was also definitely established that through either some phase of the fabrication process, possibly sintering, or the mechanics of conditioning, emission in a hard vacuum environment varied from lot to lot.

Further cathode work should be centered in the following areas:

(1) In the last few years, the advance of high temperature materials has been considerably stepped up. An extensive survey of this field should be made in the search for more reliable and efficient cathode heater devices. At this facility, under a company-financed cathode program, such an investigation has resulted in the development of a heater element which shows great potential. A report on this unit will be soon forthcoming.

(2) An efficient mercury feed system which will enable the multi-engine array to function properly should be vigorously sought. Such an effort would continue to be consistent with the overall engine program, part of which is now concerned with actual engine cluster operations.

(3) A program should be initiated which will correlate the emitting characteristics of the nickel matrix cathodes in vacuum with those in a controlled mercury environment. The program would include a number of material, configurational, and process variations. The results to date of the aforementioned company-sponsored cathode program indicate that the products of such variations could be individually matched to specific missions.

(4) Surface inspection of those nickel matrix cathodes which operated continuously in the mercury environment revealed no deleterious sputtering effects on the emitter itself. Material loss from this cause would appear to be comparable to sublimation weight losses of the emission chemicals themselves under operation at 50 volts; i. e., no measurable weight loss was incurred in samples running continuously at 2 amperes and 50 volts in Hg for periods of 140 hours.

## 8. REFERENCES

1. Ion Physics Corporation Staff, "Report on Cathode Development Studies," Contract NAS8-858, May 1962.

2. Ion Physics Corporation Staff, "Cathode Development Studies for Arc and Bombardment-Type Ion Engines," Contract NAS8-2513, April 1963.

3. Ion Physics Corporation Staff, "Low Current Density Ion Engine Development," Contract NAS8-1684, January 1963.

4. Ion Physics Corporation Staff, "Quality Program Plan for Cathode Lifetime Studies Program," Contract NAS3-3563, June 1963.

5. Kaufman, H. R., "An Ion Rocket with an Electron-Bombardment Ion Source," NASA TND-585, January 1961.

6. Jailer, R. W. et al, "Flight Vehicle Power Systems Reliability Criteria," Technical Report No. ASD-TR-61-736, Contract No. AF33 (616)-7273, March 1962.

## APPENDIX A

## CATHODE LIFETIME STUDIES – NAS 3-3563
## SINTERING PROCEDURE

New England Metallurgical Corporation, 475 Dorchester Avenue, South Boston 37, Massachusetts, will supply the sintering furnace, operator, and the furnace chart recording the time and temperature of the heat treat cycle.

Ion Physics Corporation will supply material, nickel tray, and technician.

1. Parts will be placed in a nickel tray by the IPC technician.
2. The entrance dew point of hydrogen into a pusher-type hydrogen furnace shall be -60°F or better.
3. The firing tray will be placed in the pre-heat at 400°F ±25°F and held for 30 minutes.
4. Firing tray will then be placed in the heating chamber at 2010°F ±10°F and held for 60 minutes.
5. Firing tray will then be placed in a water-jacketed hydrogen atmosphere cooling chamber whose temperature will be less than 120°F and cooled to below 150°F in 30 minutes.
6. Firing tray will then be removed from the cooling chamber and inspected by IPC technician.

## APPENDIX B

## CATHODE LIFETIME STUDIES - NAS3-3563
## CONDITIONING SCHEDULE

### General Comments

Before any tests are begun, the test operator must have a complete understanding of the test procedures. It will be the responsibility of the project leader to explain the procedures to the test operator. During the tests a copy of this schedule must be in the test operator's possession.

In addition to the recording of data explicitly called out, such as heater voltage and heater current, the test operator must also, on the conditioning test sheet, note any physical action such as turning off the diffusion pump heater or turning off the cooling water.

As a general rule, these two things must always be observed. First, whenever the system is not under hard vacuum, all power supplies must be disconnected from the main power lines. Second, the cooling water to the test chambers should be turned on only while the system is under vacuum and turned off one half hour after power has been removed from the cathode heaters.

### Procedure

The system will be assembled first without anodes. Before power is applied to the cathodes, the system will be under hard vacuum for 12 to 72 hours. At some time between a 0800 hour and 0900 hour, of the same day, power will be applied to all cathodes.

Heater power will first be applied to Position One, and then within a few seconds, power will be applied to Position Two, and so on, until power has been applied to each cathode. The power increases will be in steps of 1/2 ampere. Heater voltage, heater current, and pressure will be recorded before each power increase. The time between power increases for any particular cathode will be 15 minutes. However, if after the last set of power increases the pressure rises to the $10^{-4}$ mm range, no additional power increases will be made until the pressure drops into the $10^{-5}$ torr range. As each cathode reaches a surface temperature between 1050 and 1075°CB, it will receive no further power increases. After all the cathodes have reached the indicated temperature range, the cathodes will be held in the indicated temperature range for one hour. Heater voltage, heater current, pressure and temperature will be recorded before and after the one hour period.

The above procedure, unless otherwise noted, will be used for all heater power increases or decreases.

After the measurements have been taken, the heater powers will be decreased in steps of 1 ampere. No measurements will be recorded during the descent. One half hour after the heater powers have been completely removed, the pressure will be recorded. At 0400 the following morning the diffusion pump heater will be turned off. At 0600 the refrigeration unit will be turned off. (It will be the duty of the test technician to notify maintenance that the last two items must be performed by the night watchman. The notification must be before 1200. The test technician will also be responsible for connecting the nitrogen gas supply to the system after the heater powers have been turned off.) At 0800, the system will be purged with nitrogen gas and opened to the atmosphere. Anodes will be then placed around each cathode. At 0930, the system will be placed under hard vacuum. At 1100, and provided the pressure is below $5 \times 10^{-5}$ torr, heater power will be applied to all cathodes. The time between power increases will be 5 minutes. The temperature range to be reached will be 1000 to 1025°CB. During the power ascent, only pressure will be recorded, and then at 5 minute intervals.

At the close of the one hour period, and after all measurements have been taken, and provided the pressure is in the $10^{-6}$ torr region, each cathode will be subjected to an emission test. Only one cathode at a time, starting with Position One, will be tested. The Regatron power supply will be used. Potential between the cathode and the anode will be in 15-volt steps. The voltage drops and their associated emission currents will not be recorded on the Conditioning Test data sheets but will be directly plotted on specially prepared graph sheets. The voltage will be increased until the saturation current is reached at which point the voltage will be returned to zero. (It will be evident that the saturation current has been reached by either a zero $I_b$-$E_b$ slope or a negative $I_b$-$E_b$ slope.) However, if either the emission current reaches 400 ma or the emission power reaches some power level between 40 and 45 watts, the voltage is not to be increased any further but is to be returned immediately to zero. The period between voltage increases should be on the order of seconds. After all the cathodes have been tested, heater currents, heater voltages, temperature and pressure will be recorded.

The above procedure, unless otherwise noted, will be used for any emission test.

After the measurements have been recorded, the heater powers will be increased. The time between power increases will be 5 minutes. The temperature range to be reached will be 1050 to 1075°CB. During the power ascent, only pressure will be recorded, and then at 5 minute intervals.

At the close of the one hour period, and after all measurements have been taken, each cathode will be subjected to an emission test. After all the cathodes have been tested, the diodes will all operate in parallel off of the Regatron power supply. The potential will be set at 15 volts and both the voltage and the total emission current will be recorded in the Position One column. Heater currents, heater voltages, temperatures and pressure will be recorded. At some time between 0800 hours and 0900 hours of the following day, heater currents, heater voltages, temperatures, pressure, emission voltage and emission current will be recorded. If the emission voltage has changed and after it and the current have been recorded, the voltage will be adjusted to 15 volts and it and the current will be recorded. Each cathode will then be subjected to an emission test.

After all measurements have been recorded, the heater power will be decreased. The time between power decreases will be 5 minutes. During the power descent, no measurements will be recorded. The temperature range to be reached will be 1000 to 1025°CB. The temperature of each cathode must be within 10° of the temperature previously reported for the particular cathode in that temperature range.

At the close of the one hour period, and after all measurements have been taken, each cathode will be subjected to an emission test.

After all measurements have been recorded, the heater power will be decreased. The time between power decreases will be 5 minutes. During the power descent, no measurements will be recorded. The temperature range to be reached will be 950 to 975°CB. The temperature of each cathode must be within 10° of the temperature previously reported for the particular cathode in that temperature range.

At the close of the one hour period, and after all measurements have been taken, each cathode will be subjected to an emission test.

After all the measurements have been recorded, the heater powers will be decreased in steps of 1 ampere. The time between power decreases will be 2 minutes. One half hour after the heater powers have been completely removed, the pressure will be recorded and the diffusion pump heater will be turned off. One hour after the heater has been turned off, the refrigeration system will be also turned off. After an additional two hours, the system will be purged with nitrogen gas and opened to the atmosphere. The cathodes will be immediately removed and placed in their proper containers. The containers will then be placed in a vacuum desiccator.